VOL. 85 AT4 ASCE AIR TRANSPORT DIVISION OCTOBER 1959

VOLUME 85 NO. AT4
OCTOBER 1959

JOURNAL of the

Air Transport Division

PROCEEDINGS OF THE

AMERICAN SOCIETY OF CIVIL ENGINEERS

BASIC REQUIREMENTS FOR MANUSCRIPTS

This Journal represents an effort by the Society to deliver information to the reader with the greatest possible speed. To this end the material herein has none of the usual editing required in more formal publications.

Original papers and discussions of current papers should be submitted to the Manager of Technical Publications, ASCE. Authors should indicate the technical division to which the paper should be referred. The final date on which a discussion should reach the Society is given as a footnote with each paper. Those who are planning to submit material will expedite the review and publication procedures by complying with the following basic requirements:

1. Titles should have a length not exceeding 50 characters and spaces.

2. A 50-word summary should accompany the paper.

3. The manuscript (a ribbon copy and two copies) should be double-spaced on one side of 8½-in. by 11-in. paper. Papers that were originally prepared for oral presentation must be rewritten into the third person before being submitted.

4. The author's full name, Society membership grade, and footnote reference stating present employment should appear on the first page of the paper.

5. Mathematics are reproduced directly from the copy that is submitted. Because of this, it is necessary that capital letters be drawn, in black ink, ⅛-in. high (with all other symbols and characters in the proportions dictated by standard drafting practice) and that no line of mathematics be longer than 6½-in. Ribbon copies of typed equations may be used but they will be proportionately smaller on the printed version.

6. Tables should be typed (ribbon copies) on one side of 8½-in. by 11-in. paper with a 6½-in. by 10½-in. invisible frame. Small tables should be grouped within this frame. Specific reference and explanation should be made in the text for each table.

7. Illustrations should be drawn in black ink on one side of 8½-in. by 11-in. paper within an invisible frame that measures 6½-in. by 10½-in.; the caption should also be included within the frame. Because illustrations will be reduced to 69% of the original size, the capital letters should be ⅛-in. high. Photographs should be submitted as glossy prints in a size that is less than 6½-in. by 10½-in. Explanations and descriptions should be made within the text for each illustration.

8. Papers should average about 12,000 words in length and should be no longer than 18,000 words. As an approximation, each full page of typed text, table, or illustration is the equivalent of 300 words.

Further information concerning the preparation of technical papers is contained in the "Technical Publications Handbook" which can be obtained from the Society.

This Journal is published by the American Society of Civil Engineers. Publication office is at 2500 South State Street, Ann Arbor, Michigan. Editorial and General Offices are at 33 West 39 Street, New York 18, New York. $4.00 of a member's dues are applied as a subscription to this Journal.

Subject and author indexes, with abstracts, are published at the end of each year for the Proceedings of ASCE. The index for 1958 was published as Proc. Paper 1891; indexes for previous years are also available.

AT,CP,CO,SU,PL,PP.

Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

CONTENTS

October, 1959

Papers

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

LONGITUDINAL DISTRIBUTION OF WHEEL LOADS ON A RUNWAY

R. W. Smith[1] and R. Horonjeff,[2] F. ASCE

SYNOPSIS

This paper examines existing runways in the light of the jet age, and analyses the economy factors in runway construction.

INTRODUCTION

Objective

The objective of this paper was to investigate the manner in which aircraft loads applied to a runway vary in a longitudinal direction. The paper presents a rational basis for determining these loads and their effect on pavement thickness. The maximum applied loads occur at the take-off end of a runway where the aircraft is either stationary, or moving slowly, with little or none of its weight being supported by the wing. As the aircraft accelerates and moves down the runway for take-off an increasing portion of its gross weight is transferred from the landing gear to its wings. Likewise the weight of an aircraft which is landing is normally less than its weight on take-off. Thus a portion of the runway does not have to carry the full weight of the aircraft but only a fraction of it.

It is intended to set forth in this report a general method of establishing the loads on the various portions of the runway imposed by take-off and landing aircraft. The total load transmitted via the landing gear of an aircraft to the runway pavement at any given instant and at any given location during take-off or landing operations depends on a number of variables. Some of these

Note: Discussion open until March 1, 1960. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 2189 is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 10, No. AT 4, October, 1959.

1. Aircraft Engr., Flight Eng. Div., United Air Lines, Inc., San Francisco, Calif.

2. Prof. of Transportation Eng. and Research Engr., Inst. of Transportation and Traffic Eng., Univ. of California, Berkeley, Calif.

variables can be calculated with some certainty while others can only be estimated by judgment and with the background of operational experience as a guide.

Take-Off and Landing Weights

Obviously, the take-off and landing weights of aircraft will be the basic factors of concern in any pavement design analysis. In developing the method in this paper the maximum take-off gross weight and the maximum structural landing weight, both determined by the aircraft manufacturer, are assumed throughout. While this assumption does not affect the development of the method, it should be borne in mind that for a specific airplane at a specific airport the maximum take-off weight should not be assumed. Rather, the take-off and landing weights should be estimated as closely as possible, taking into account all factors which affect weight.

Take-off Weight.—The take-off weight for a specific type of aircraft is dependent on (1) the amount of revenue producing load commonly termed pay-load (2) the length of the trip (3) enroute wind and temperature conditions (4) speed and altitude at which aircraft is to be operated and (5) amount of reserve fuel carried.

Landing Weight.—Landing weight equals take-off weight minus the weight of fuel used on the trip. However, on a long trip, the landing weight is so much less than the take-off weight that, for the purposes of pavement design, it would never be the limiting factor. The landing weight that will be considered, as mentioned earlier, is the maximum landing weight which is dictated by the structural limitations of the aircraft. The assumption of this maximum weight actually provides a sort of "built-in" safety factor since landing at, or near, this weight would occur under only two conditions: One occurs when a heavily loaded aircraft makes an intermediate stop on a long range flight so that it lands with a very heavy fuel load. This case will account for most high weight landings and will occur at intermediate stations and not at terminal points. The other case of high weight landing would be an emergency when the aircraft is forced to land soon after take-off as a result of some malfunction. In this case fuel jettisoning might be used to reduce the weight rapidly to avoid landing at over the manufacturer's specified maximum landing weight. Landings in this emergency condition are possible but highly infrequent.

Factors Affecting Distribution of Weight Along Runways

Once the weight of the aircraft is determined there are other factors which will affect the pattern of application of this weight to the runway.

Engine Performance.—The rate at which the aircraft accelerates for take-off is dependent, for a given weight, on the engine output or performance. It is an accepted fact of aircraft operation that this performance is not constant, even for a constant temperature; however, under normal circumstances it will not vary over 2 or 3%. All values used in this report have been based on operational performance calculated by the aircraft manufacturers at the engine manufacturers' power plant ratings. In applying the analysis to a specific airport it would be necessary to have the aircraft operational data corrected to the proper altitude and air temperature.

Aircraft Configuration.—The most important factor of aircraft configuration affecting the distribution of weight along the runway as the airplane accelerates is the airfoil. The lift of the wing at any given speed will be directly

proportional to the lift coefficient, a dimensionless factor dependent on the shape of the airfoil. The equation for lift is:[1]

$$L = C_1 \, Sq$$

where: L = lift (pounds)

C_1 = lift coefficient (dimensionless)

q = dynamic pressure (lbs/sq. ft.) $= \frac{\rho v^2}{2}$

Appendix A demonstrates how this relationship is used to determine, for a specific aircraft, that portion of total weight being carried by the wings.

Pilot Technique.—Pilot technique during landing determines the point of touchdown and, to some extent, the length of landing rollout. Both of these factors may also be influenced by the location of exit taxiways and the intended destination on the ramp or other part of the airport.

Airport Factors

For a specific airport location those variables affecting aircraft performance are: the altitude of the airport, the surface wind velocity and direction, temperature, barometric pressure, and runway gradient. For the purpose of this paper the following assumptions are made:

1. Airport altitude	Sea level
2. Wind velocity	No wind
3. Temperature	59° F.
4. Barometric pressure	29.92" of mercury
5. Effective runway gradient	Zero

Development of Method

Types of Aircraft Considered

Using the basic information presented in the preceding section it is possible to develop a general method for investigating the manner in which aircraft loads applied to a runway vary in a longitudinal direction. It should be kept in mind that the method can be applied to any aircraft and any airport location. The aircraft considered as examples in this report were chosen to cover a wide spectrum of weight and payload capabilities. All are in use, or scheduled for use by 1960, by the major airlines of the United States.

Convair 340:	twin-engine, propeller driven
DC-6B:	four-engine, propeller driven
DC-7:	four-engine, propeller driven
DC-8:	four-engine, jet transport (domestic version)
707-320:	four-engine, jet transport (intercontinental version)
Lockheed Electra:	four-engine, prop-jet

The performance characteristics of these aircraft are listed in Table 1.

TABLE 1 — CHARACTERISTICS OF AIRCRAFT USED IN ANALYSIS*

	CV-340	DC-6B	DC-7	DC-8	707-320	Electra
Maximum take-off weight (lb)	47,000	107,000	122,200	265,000	295,000	116,000
Maximum landing weight (lb)	46,500	85,000	97,000	189,000	195,000	95,650
Maximum take-off gear load	18,000	40,000	46,500	118,000	135,000	52,000
Maximum landing gear load	17,750	32,000	42,000	84,000	89,000	43,000
Lift off speed (knots)	106	116	125	155	158	124
Lift off distance (Feet)	2,500	3,200	3,300	6,600	7,800	3,200
Tire pressure (psi)*	69	106	123	150	148	132
Type main gear	Dual	Dual	Dual	Dual Tandem	Dual Tandem	Dual

*Approximate values given in table.

Load vs Take-Off Distance

Fig. 1 has been drawn using the assumptions outlined in the Introduction. It shows, for each aircraft, the steadily decreasing load carried by the main gear of the airplane as it accelerates during take-off. In order to arrive at this curve of Load vs Take-Off Distance it is necessary to have operational performance at the desired take-off weight for each aircraft. Appendix A outlines in detail for one of the aircraft the steps required to translate this performance data into a pattern of runway loading.

This pattern was assumed to start at the end of the runway since, in most instances, aircraft make use of the full available length of runway for take-off.

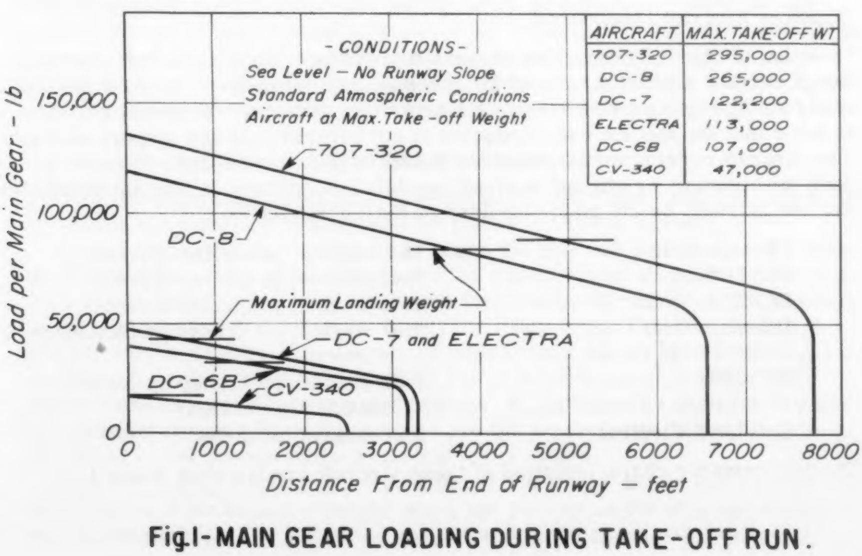


Fig.1-MAIN GEAR LOADING DURING TAKE-OFF RUN.

The horizontal lines intersecting each Load vs Take-Off Distance line indicate the main gear load at the maximum landing weight. It is true that the loads applied to the main gear during landing form an envelope similar to the take-off Load vs Distance envelope. Contrary to the take-off case which has a fixed point of departure however, the landing Load vs Distance envelope cannot be located along the runway with any reliability. A study by the Civil Aeronautics Administration has shown that points of touchdown are scattered over at least the first 2,000 feet of runway with no definable pattern other than that the majority are in the first 1,000 feet.[2] Also, as pointed out in the Introduction, pilot technique, taxiway location, and eventual airport destination may influence both point of touchdown and roll out distance. For these reasons it may be assumed that practically the entire length of the runway may be exposed to the landing weight. The maximum landing weight may, therefore, be the heaviest load expected on those sections of runway which lie beyond the intersection of the Load vs Take-Off Distance curve and the line of maximum landing weight.

Ratio of Maximum Landing Weight to Maximum Take-Off Weight

Table 2 compares the maximum take-off weight and the maximum landing weight for each aircraft.

TABLE 2 – MAXIMUM LANDING WEIGHT AS A PERCENTAGE OF MAXIMUM TAKE-OFF WEIGHT

Aircraft	Maximum take-off weight	Maximum landing weight	% of Maximum take-off weight
CV-340	47,000	46,500	99
DC-6B	107,000	85,000	79
Electra	116,000	95,650	82
DC-7	122,200	97,000	79
DC-8	265,000	189,000	71
707-320	295,000	195,000	66

It is significant that in general, the per cent difference between these two values increases as the maximum take-off weight increases. This is due to the fact that a greater portion of weight is given over to fuel load in the heavier, longer range aircraft.

Reduction in Gear Load

Fig. 2 has been drawn to show the reduction in runway loading with distance in terms of per cent of the maximum take-off weight for each aircraft. This type of presentation points up an interesting and important difference in performance between propeller powered and jet powered aircraft. The slope of the unloading curve for each aircraft is an indication of the rate at which load reduction takes place. As is shown in Appendix A, the load reduction at any given point depends on the speed of the aircraft at that point (as accounted for by the dynamic pressure factor in the given equation). The slope of the unloading curve for each airplane is therefore an indication of the acceleration

of that airplane. It is obvious from Fig. 2 that the two jet powered aircraft have very similar acceleration characteristics and that these are very much slower than those of any of the propeller powered aircraft. This fact is well known and of great importance to the aircraft engineer and, as this analysis will show, may also be of importance to the airport engineer.

Analyzing the effect of the two factors just noted; the ratio of maximum landing weight to maximum take-off weight, and the slope of the Load vs Take-Off Distance curve, a possible pattern for design may be seen. The heavy lines in Fig. 2 are runway load envelopes based on the characteristics of the two types of aircraft, propellor and jet powered. It is evident that the load on the runway varies considerably with distance and, also, that the two load envelopes are significantly different. These facts lead to the idea that runway strength, i.e. thickness, might be allowed to vary using the proper load envelope as the design criteria.

Reduction in Pavement Thickness

Fig. 3 shows the thickness of flexible runway pavement (designed according to the Corps of Engineers CBR method) which is required to support the aircraft gear loads shown in Fig. 1. (The CV-340 will be omitted from the remainder of the analysis since it is improbable that an aircraft this small would be the critical one at a large civil airport.) Appendix B explains how the thicknesses in Fig. 3 were determined.

The thicknesses are shown, for any given distance, in terms of per cent of maximum thickness required. The similarity between these curves and the

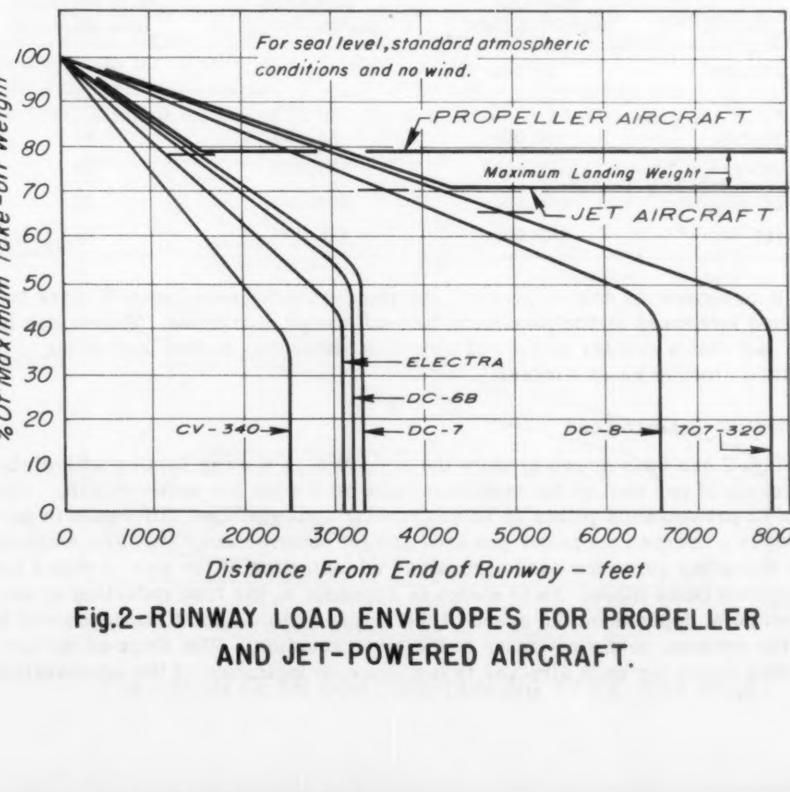


Fig.2-RUNWAY LOAD ENVELOPES FOR PROPELLER AND JET-POWERED AIRCRAFT.

ones in Fig. 3 is obvious. Just as an envelope could be drawn for each type of aircraft runway loads in Fig. 2, so can a similar envelope of required pavement thickness be drawn as in Fig. 3.

An interesting comparison can be made in Fig. 3. The dashed line which has been plotted in this figure represents the present Corps of Engineers criteria for thickness. That is, the first thousand feet of runway is designed for maximum static aircraft weight and the thickness of the central portion of the runway is then reduced by 10%. Fig. 3 shows that for propeller driven aircraft this is a good rule-of-thumb design. There is close agreement between the thickness envelope at the level required by the maximum landing weight and the thickness envelope drawn according to the Corps of Engineers' rule.

However, comparing the thickness envelope generated by the jet aircraft with that of the Corps of Engineers criteria reveals two facts of importance. First, due to the slow acceleration characteristics already noted for the jets, the runway load has not been decreased sufficiently to allow a decrease in pavement thickness of 10% at a point only 1,000 feet from the end of the runway. Second, due to the lower ratio of maximum landing weight to maximum take-off weight for the jets, as shown in Table 2, the 10% reduction actually results in an over-design of the central portion of the runway—that is, more thickness than is actually required.

Therefore, for those runways which will be designed to support jet transport operations, it would appear that an overall benefit might be gained by considering these two factors. In the first place, if the rule of 10% reduction in thickness is adhered to, it might be well to investigate whether this transition should be made 2,000 feet from the end of the runway instead of only 1,000 feet from the end. In the second place, it would appear that a second

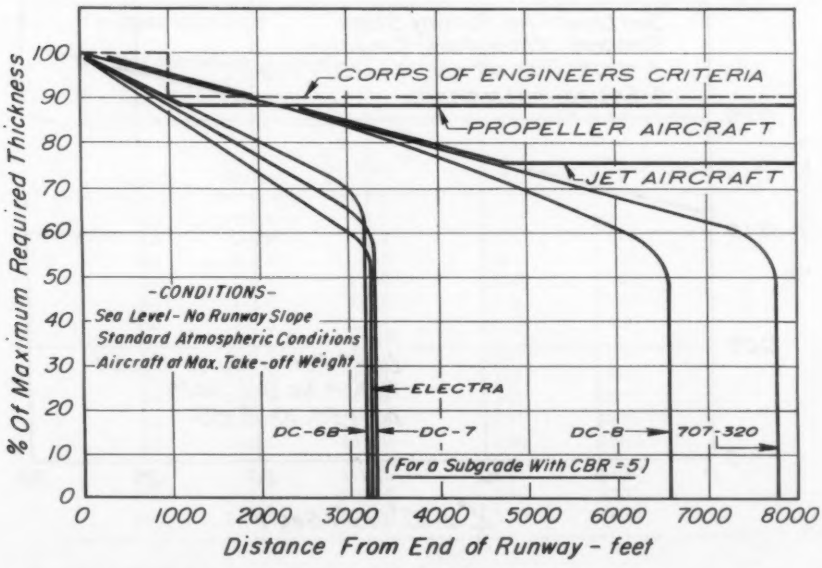


Fig.3-RUNWAY THICKNESS ENVELOPES FOR PROPELLER AND JET-POWERED AIRCRAFT.

reduction in thickness is feasible at a point about 4,500 feet from the end of the runway for those runways which are predominantly used in one direction. Since the thickness of pavement required would be based on the heavier jet aircraft, this second reduction would not result in an under-design for the lighter propeller driven aircraft using the same runway. The above observations are made on the assumption that instantaneous static loads govern the thickness of the runway. As an aircraft accelerates down a runway, the load on the pavement decreases as the speed increases. The load is therefore not a static one and, as the speed increases, the "effective load" on the pavement, insofar as stresses are concerned, is probably less than the load computed by the method presented in this paper. This point may be worthy of investigation by field tests.

Whether the use of such a design method would result in any economies would depend on the location of the specific airport, the total length of runway required, availability of materials, etc. However, it is believed that even if no economies resulted, the placement of material according to this method would result in a more rational and balanced design according to the runway requirements and would therefore be worthwhile.

CONCLUSIONS

As a result of the foregoing analysis, the following conclusions are felt to be valid:

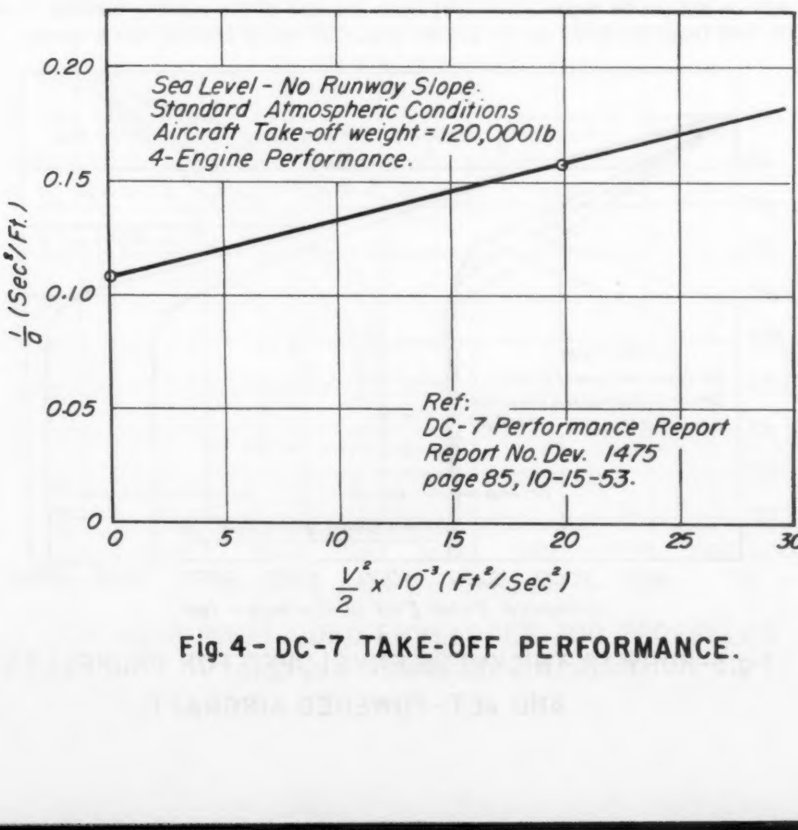


Fig. 4 - DC-7 TAKE-OFF PERFORMANCE.

1. The variation of aircraft loads in a longitudinal direction on a runway may be analyzed with sufficient accuracy to provide data for required runway thickness.
2. The rate of decrease in wheel loading of jet-powered aircraft is significantly slower than that for propeller-driven aircraft. This fact should be considered if criteria for variable runway thickness in a longitudinal direction are to be considered.

APPENDIX A

Calculation of Gear Load vs Distance

Fig. 4 is an example of the airplane performance information for the DC-7 supplied by the manufacturer.[3] This straight-line graph, developed from actual aircraft tests and instrumentation, furnishes the basic data required to determine the load on the main landing gear at any point along the runway for a given aircraft take-off weight. The following table shows the preliminary step of determining the distance from the start of take-off. It is possible to enter Fig. 4 with either assumed values of $\frac{V}{2} \times 10^{-3}$ or $\frac{1}{a}$ and to read the other value directly from the graph. Since most aircraft operational data is given in terms of knots, the first step in this example was to choose points every 10 knots, and calculate the corresponding aircraft weights. Calculation of the acceleration distance is by the formula:

$$S = \frac{1}{a} \times \frac{V^2}{2}$$

where: S = distance (feet)

a = acceleration (feet/sec^2)

V = speed (feet/sec)

Knots	Ft/Sec	$\frac{V^2}{2} \times 10^{-3}$	$\frac{1}{a}$	S
0	------	-----	----	----
10	16.9	.14	.109	15
20	33.8	.57	.110	65
30	50.7	1.29	.112	145
40	67.6	2.29	.115	265
50	84.5	3.57	.117	420
60	101.4	5.15	.121	625
70	118.3	7.01	.126	885
80	135.2	9.15	.131	1200
90	152.1	11.55	.137	1585
100	169.0	14.30	.144	2060
110	185.9	17.25	.151	2600
120	202.8	20.60	.159	3250
130	219.7	24.10	.168	4050

Speed vs Distance is plotted in Fig. 6.

Knowing the lift coefficient, C_1, for the airfoil, the lift developed by the wing is computed using the formula:

$$L = C_1 Sq$$

where L = lift (pounds)

C_1 = lift coefficient (dimensionless)

S = wing area (sq. ft.)

q = dynamic pressure $q = 1/2\, \rho\, V^2$, lbs/sq. ft.)

ρ = density (.002378 lb sec^2/ft^4 at sea level)

For the DC-7, C, for take-off configuration is 0.85 and the wing area is 1,462 sq. ft. The coefficient of lift C_1 used in the computations corresponds to the condition of high speed taxiing with all wheels on the pavement. After the nose gear is rotated, the angle of attack increases materially and the coefficient is much higher (e.g. DC-7 C_1 = 1.52). Twenty-four per cent of the total aircraft weight is carried by the nose gear and 38% of the total carried by each main gear. By subtracting the lift at any speed from the total take-off weight and multiplying this difference by 0.38, the load per main gear is found.

Load per Main Gear vs Speed is plotted in Fig. 7. By cross-plotting Figs. 5 and 6, or by using the table above, the desired relationship, Load per Main Gear vs Distance, is obtained as shown in Fig. 7.

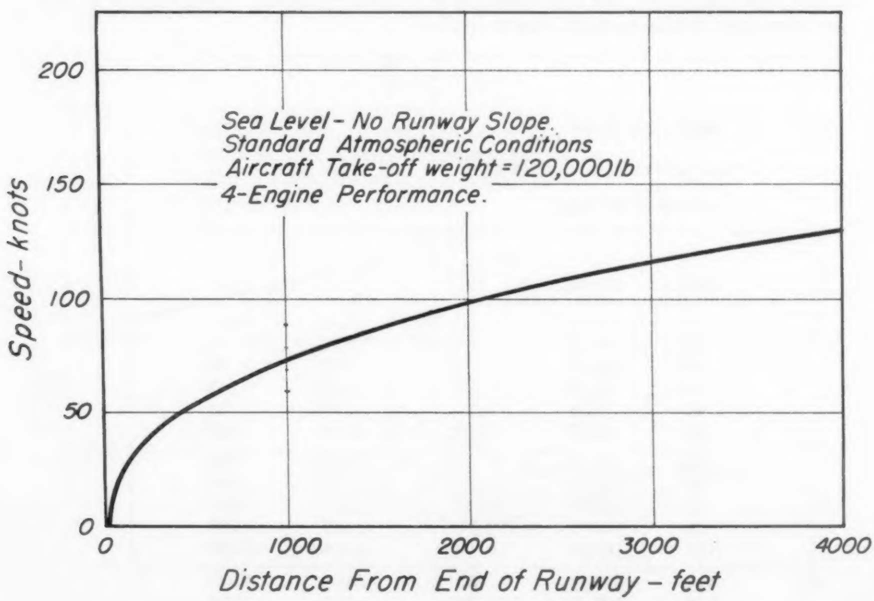


Fig. 5 - DC-7 TAKE-OFF PERFORMANCE.

Knots	Lift (lb)	Weight - Lift (lb)	Load per Main Gear (lb)
0	0	120,000	45,500
10	420	119,780	45,300
20	1,690	118,310	44,900
30	3,800	116,200	44,200
40	6,750	113,250	43,100
50	10,550	109,450	41,600
60	15,200	104,800	39,800
70	20,700	99,300	37,700
80	27,000	93,000	35,300
90	34,100	85,900	32,600
100	42,200	77,800	29,600
110	51,100	68,900	26,200
120	60,700	59,300	22,500
130	71,200	48,800	18,500

APPENDIX B

Runway Thickness by the Corps of Engineers Method

The Corps of Engineers uses the California Bearing Ratio (CBR) method in the design of flexible pavements. This method uses an index (CBR) of strength obtained in a penetration-type shear test. This index has been related to a family of curves (CBR design curves) derived from service behavior correlations.(4) Special methods of dealing with the multiple-wheel landing gear

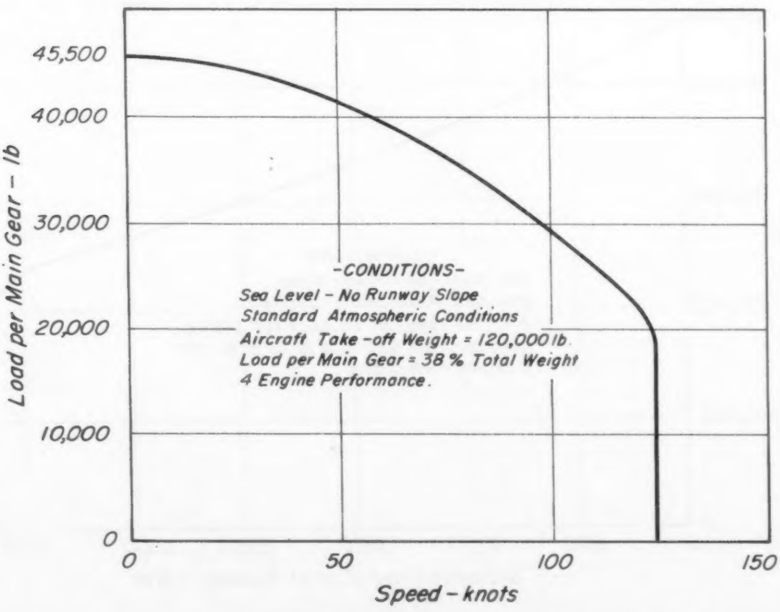


Fig.6 - DC-7 TAKE-OFF GEAR LOAD vs SPEED.

configurations of heavy aircraft of the type considered in this report, have also been devised by the Corps of Engineers.(4)

Boeing Airplane Company has published a technical report in which they present a design chart derived from those developed by the Corps of Engineers which can be used for any combinations of landing gear configuration, wheel loads, subgrade CBR, and tire pressure.(5) Because of the convenience of this presentation, this chart was used in computing thicknesses (at points in multiples of 1,000 feet from the end of the runway). The procedure was as follows: First, the load per main gear was read directly from Fig. 1. Then the ESWL (equivalent single wheel load) and the thicknesses were obtained from the CBR chart shown in the Boeing report.(5) The thickness of flexible pavement was calculated for a subgrade CBR of 5. The per cent column in the tables below shows the relationship of thickness at a given point to the maximum thickness required for a specific aircraft. This information was then plotted in Fig. 3.

REFERENCES

1. Dwinell, James H., Principles of Aerodynamics, McGraw-Hill Book Company, Inc., 1949.

2. Civil Aeronautics Administration, Airport Engineering Bulletin No. 1, Office of Airports, Washington, D. C.

3. Douglas Aircraft Company, Inc., DC-7 Performance Report, Report No. Dev. 1475, p. 85, November 15, 1953.

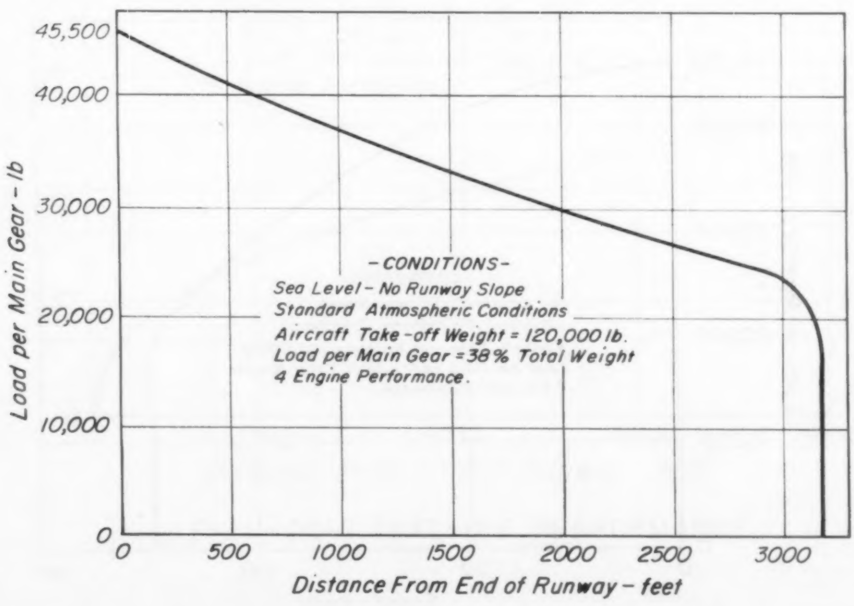


Fig.7-DC-7 TAKE-OFF GEAR LOAD vs DISTANCE.

4. "Development of CBR Flexible Pavement Design Method for Airfields", Transactions, American Society of Civil Engineers, Paper No. 2406, v. 115, 1950.

5. Boeing Airplane Company, Airport Strength Requirements Boeing Model 707 Jet Transport, Document No. D-17322, September 30, 1955.

Propeller Driven Aircraft:

	Distance[1]	Load per Main Gear (lb)	ESWL[2]	Thickness (in.)	% of Max. Thickness
DC-6B	0	40,000	26,400	24	100
	1000	34,000	21,500	21	89
	1300*	32,000	20,000	21	
	2000	27,500	16,800	18	75
	3000	21,200	12,300	16	68
DC-7	0	46,500	32,000	26	100
	750*	42,000	28,200	24	92
	1000	39,000	25,500	23	89
	2000	32,000	20,000	21	81
	3000	25,500	15,400	18	69
Electra	0	51,000	42,000	30	100
	1000	40,500			
	1500	37,000	26,500	24	80
	2000	32,500			
	3000	28,500	16,000	18	60

Jet Powered Aircraft:

	Distance[1]	Load per Main Gear (lb)	ESWL[2]	Thickness (in.)	% of Max. Thickness
DC-8	0	118,000	65,000	38	100
	1000	109,000	58,000	36	95
	2000	99,000	52,000	34	90
	3000	89,000	45,000	32	84
	3700*	84,000	41,000	30	79
	4000	80,000	38,500	29	76
	5000	72,000	31,000	26	69
	6000	64,000	24,000	23	61
707-320	0	135,000	70,000	40	100
	1000	125,000	62,500	38	95
	2000	116,000	57,000	36	90
	3000	107,000	50,500	34	85
	4000	98,000	45,000	32	80
	4800*	89,000	39,500	29	73
	5000	88,000	39,000	29	73
	6000	78,000	34,000	27	68
	7000	69,000	28,500	25	63

1. Distance in feet from start of roll
2. ESWL: Equivalent single wheel load - computed by Corps of Engineers procedure.
* Point at which load per main gear is same as at maximum landing weight.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

LOS ANGELES INTERNATIONAL AIRPORT

Frank A. Grainger[1]

In 1926 the City of Los Angeles was considering the establishment of a municipal airport. With this end in view a group of citizens headed by Judge Frank D. Parent of Inglewood started a search for a location. They wisely employed Dr. Ford A. Carpenter a meteorologist to make a survey of the area. Dr. Carpenter's report to City and airline officials indicated that the most nearly perfect conditions of even temperatures, low humidity and wind velocity and dependable wind direction prevailed at a 640 acre section of a ranch belonging to Andrew Bennet. This survey and report resulted in the City of Los Angeles leasing the 640 acre tract for a period of fifty years. In 1937 the City purchased the property and have since purchased additional acreage, bringing the total to 3000 acres.

In 1928 when the airport, known as Mines Field, was leased by the City, the landing strip was unpaved and approximately 2000 feet long. Shortly after the City leased the property the landing strip was oiled. This treatment consisted of a single application of penetration type asphalt, a treatment that would not be considered a good dust palliative by today's standards.

Over the years this original strip has been lengthened and widened, other runways have been constructed and taxiways added until, in 1958, the system consisted of the two parallel east-west runways 8500 feet long with supporting taxiways and warm-up aprons and one north-south runway 4400 feet long.

The Master Plan prepared by the Joint Venture under the current contract shows, in addition to the new terminal work, the existing two east-west runways to be lengthened to 10,000 feet and the addition of high-speed exit taxiways. Lengthening the north-south runway to 6500 feet and the addition to two more east-west runways, 10,000 feet long, located approximately 4500 feet north of the existing runways. This configuration of runways with the loading and unloading gate positions between the two runways systems tend to create an aircraft traffic flow in one direction under normal operation. This one directional flow is established by using the southern (instrument) runways for landing aircraft and the northerly runways for take-offs.

The Master Plan also shows an area west of the terminal area and west of the north-south runway set aside for aircraft maintenance sites. These

Note: Discussion open until March 1, 1960. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 2190 is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 85, No. AT 4, October, 1959.

1. Project Engr., Joint Venture for the Los Angeles International Airport, Los Angeles, Calif.

maintenance sites are leased to the airlines for maintenance bases and the area is already extensively developed with American Airlines, Pan American Airlines and Continental Airlines in operation on their sites and construction of facilities for T.W.A. nearing completion.

The first phase of a contract to construct one of the northerly (take-off) runways with supporting taxiways has been completed and the second phase will be started in March or April of this year depending upon the completion of the Lincoln Boulevard re-routing now under construction.

At the start of design, a very detailed study was made of existing and proposed future aircraft characteristics in order to establish design criteria for runway and taxiway pavements and sub-surface structures. In determining a design load to be used in the design it was found that the equivalent single wheel load imposed by the DC-8, at 287,500 lbs. gross, was much less than that caused by the Boeing Stratocruiser 377 at 142,000 lbs. gross, due of course to the dual tandem type gear of the DC-8.

It was also found to be a unanimous opinion of plane manufacturers that while aircraft of the future may exceed the DC-8 or Boeing 707 in gross weight the equivalent single wheel load could and would be held more or less constant by altering the characteristics of the gear.

The findings of this study were made known to the Department of Airports and to the Civil Aeronautics Administration along with our recommendation that the CAA required 100,000 design wheel load for Inter-Continental Express airports be reduced to a more realistic figure. A similar study, made by the CAA, later corroborated our conclusions and the Joint Venture was instructed to reduce the design wheel load to 60,000 pounds. This reduction decreased the thickness of the Portland cement concrete pavement three inches, representing a substantial money savings.

A soil survey performed by the Donald R. Warren Company indicated excellent subgrade material throughout with only a few local deposits of blow sand and clay which were removed and replaced by selected material from the excavations. All of the subgrade fell within C.A.A. Classifications E-1 and E-2.

Pavement thicknesses were taken from C.A.A. curves and are as follows:

Portland cement concrete taxiways and end 500' runways - 12"
Asphaltic concrete runway pavement, non-critical areas - 2" of A.C. on 8" of crushed rock base.
Asphaltic concrete runway pavement, critical areas - 3" of A.C. on 10" of crushed rock base.

All pavements were placed on subgrade compacted to 95% to a depth of 12".

The "High Speed Exit Taxiways" mentioned as being in the scope of the Master Plan are designed to increase the capacity of landing runways by eliminating the long deceleration runs after touchdown.

In designing the high speed exit taxiways publications of the Institute of Transportation and Traffic Engineering of the University of California were used. These publications are the results of research and tests made in a joint project between the Flight Engineering Division of ITTE and United Airlines, Inc., headed by Robert Horonjeff, Research Engineer, ITTE and Richard Coykendall, Aeronautical Engineer, U.A.L.

The high speed exit taxiways designed for the landing runways have a radius of 1800 feet and enable aircraft to safely leave the runway at speeds

approaching 60 miles per hour. This represents a savings in runway occupancy time of over thirty seconds per landing.

Storm drainage for the airport runways, loading aprons and terminal area proved interesting from the design standpoint. It was immediately apparent that any system of storm drains serving the new development must be closely coordinated with all of the storm drain studies and construction performed in the vicinity during past years under the supervision of the Los Angeles City Engineer. The most important of the recent storm drain construction in the vicinity of the airport is the perimeter drainage channel which originates near the northwest portal of the Sepulveda Boulevard tunnel. This channel picks up storm water originating in the southerly runway areas from underground conduits and runs generally parallel to the airport boundary northerly, under Century Blvd., in a box culvert, and westerly to a large ponding basin west of the west end of the new runway.

A detailed study of the hydrology of this channel showed that whereas the unlined channel, as it exists, has ample capacity to handle the run-off under present conditions of development of the tributary areas, the large areas of buildings and pavements proposed for the airport area plus further development of areas north of the airport contributing to this channel run-off would overtax its capacity. This capacity could, of course, be increased substantially by lining the entire channel. A further study of the on-site drainage areas indicated large areas of the new terminal-automobile parking area to be too low to drain into the channel under high water conditions. A comparison between lining the channel, a pump station and a new outfall resulted in choosing a new outfall which consists of a new 8'6" x 10' box culvert between the westerly end of the terminal area and a ponding basin in the vicinity of Imperial Highway and Coast Boulevard, a distance of approximately 5400 feet.

It should be mentioned that whereas the absorption rate of the ponding basins being used in this system is excellent, the development of contributing areas will in the foreseeable future necessitate an outfall through the sand dunes to the ocean.

The airfield runway and taxiway areas were the subject of an extensive study comparing open channel flow and underground conduit systems. It was agreed that an underground conduit system was desirable, allowing a much safer surface for erratic aircraft. It was, however, finally decided to design for open channels with extremely flat side slopes 10 to 1, offering a minimum of danger to out-of-control aircraft. The deciding factors of this decision were lower maintenance and construction costs.

The storm drainage design is based on the City of Los Angeles method of computing run-off. A design storm frequency of 5 years was used for airfield areas and loading apron areas; 50 year frequency was used for the terminal-automobile parking area.

The electric power serving the new terminal area, ticketing buildings and satellite buildings is furnished by the Los Angeles Department of Water and Power. The power enters the site near the intersection of Century and Sepulveda Boulevards, underground, and is transmitted to the vaults serving the various buildings in underground lines. The current serving these vaults is transmitted at 34.5 KV. The total demand estimated for this area is approximately 57,000 KVA.

The airfield lighting power is also furnished by the Los Angeles Department of Water and Power through an underground 4800-volt line running from their sub-station near Imperial Boulevard to an electrical vault near the

intersection of the north-south runway and the new east-west runway. These two systems are not connected at present but duct work is installed to interconnect the two systems in the future.

Water, both domestic and fire, are served by mains of the Metropolitan Water District. The Department of Airports has installed a 12' main through the site from a point near Sepulveda and Century Boulevards running westerly through the terminal area and through the aircraft maintenance sites, thence northerly to Manchester Boulevard. The Metropolitan Water District mains connecting both ends of this main are both high-pressure mains, ensuring an adequate water supply from either source.

Sanitary sewerage presented no particular problems. The City of Los Angeles Central Outfall Sewer runs through the terminal area, providing an easy means of disposal.

The Joint Venture is presently involved in the design of fueling systems and other utilities to be installed under the aircraft loading aprons to serve each of the ten gate positions adjacent to the Satellite Buildings. The utilities being considered in addition to fueling are air for starting jet engines, demineralized water for use with certain of the jet engines and 28-volt, high-frequency power.

The fueling systems under consideration vary with each individual airline, depending on their particular requirements and the facilities of the fuel supplier.

In general, the fueling systems will consist of pipe loops around each Satellite building serving fueling vaults placed under each wing at each gate position. These vaults will generally have aviation gasoline and jet fuel hydrants. The service loops will be served either from a tank farm, serviced by truck, near the aircraft maintenance sites or direct from oil company pipe lines through small storage tanks located underground off the north or south edge of the apron pavement.

An idea of the magnitude of each fueling system can be gained by a look at the performance required. In striving for a thirty-minute turn-around period, the goal of the airlines, it becomes obvious that the rate of fueling must exceed the capacity of any existing system.

In order to meet this time requirement the new jet aircraft are equipped to take the required 22,000 gallons of fuel through four hose connections, two in each wing, at the rate of 300 gallons per minute per connection, or a total of 1200 gallons per minute.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

ARCHITECTURAL PLANNING AND TREATMENT OF AIRPORT PROBLEMS

Donald E. Wilcox[1]

Today's metropolitan airport is faced with the challenge of the jet air age. Airport facilities throughout the country have been developed gradually over the past two decades within the framework of requirements set up by piston engine aircraft, most of which have tended to become larger, faster and more complex. As it becomes apparent that jet aircraft would be feasible for commercial passenger and cargo work, a new set of airport design criteria had to be developed. Performance and economic characteristics of the new aircraft require re-analysis of runway lengths, pavement design load factors, ground handling and service techniques. Air and ground traffic control problems and passenger handling methods have also had to be re-examined in light of changed economic conditions. Many agencies, organizations and individuals throughout the country have participated in this development.

This paper will attempt to give the highlights of the development of the Los Angeles International Airport to meet this jet age challenge.

This airport, then known as Mines Field, was established in 1928 in a 640 acre portion of the present site and consisted of one 2000 foot dirt strip. Development of the airport continued steadily over the next 15 years and brought about the establishment of the first Master Plan for the airport in 1943 showing runways of 4660 feet with provision for future expansion. Another ten years brought the airport to essentially the present state of development; temporary terminal facilities, including an air freight terminal, 8500 feet runways, and numerous maintenance hangars.

Just prior to 1953 another series of Master Plan studies prepared by Pereira & Luckman led to the disposition on the site of the major elements of the scheme now being developed. Soon after an unsuccessful attempt to obtain voter approval of a $33.5 million bond issue in 1953, the City of Los Angeles, acting through its Board of Airport Commissioners, invited Los Angeles architects and engineers to be interviewed for selection to participate in the planning and development of the airport project. The final selection consisted of three local architectural firms, Pereira & Luckman, Welton Becket and Associates and Paul R. Williams. These three firms formed a Joint Venture which has continued to function in this capacity.

Note: Discussion open until March 1, 1960. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 2191 is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 85, No. AT 4, October, 1959.

1. Vice-Pres., Charles Luckman Associates, Los Angeles, Calif.

Early in 1955 more studies, research and proposed layouts were developed, analyzed, estimated and discarded until December of that year when, all participating groups being in broad agreement, the proposed budgets were settled on, and financial plans drawn. In June of 1956 the $59,700,000 bond issue was accepted by the voters by a large majority and work on the project began in earnest. During the fall of 1956 conferences were held with Airlines staff members, Mr. Ken Osterberg, of Aviation Services Company of Minneapolis, Minnesota, acting as the Board's economic consultant, for the purpose of developing the broad elements of the program. The architects were then provided with basic design criteria developed from these conferences and the economics of the project. Earlier Master Plan studies had established the general configuration of the project with the terminal facilities being located directly west of the intersection of Century and Sepulveda Boulevards, some distance to the west of the present terminal facilities. The runway layout consisting of two pairs of offset parallel strips running generally east-west to align with the prevailing westerlies and a shorter north-south runway to accommodate traffic in the few days per year when Los Angeles has strong northerly winds, was again confirmed. Further to the west the maintenance hangar area was already being developed by American Airlines, Pan American, TWA and others.

Studies of the terminal area layout during this period lead to the conclusion that the basic concept of a high capacity parking lot as the hub of the terminal, surrounded by the various airline and public facilities was a sound one.

However, because of the economics of the problem, the multi-level parking structure around which the scheme revolved had to be modified. This brought about a condition wherein only a limited number of parking spaces could be achieved with the balance required to be located in a large parking lot rather remote from the passengers' first contact with airline service, the ticketing facilities. The solution to this particular problem developed in the form of a significantly larger (4800 car capacity) parking lot in the central area with provisions made to double-deck part or all of the area if the need arises, as it seemingly will.

Concurrently with these studies, contacts with the airline operators brought out the significant fact that because of the shortened turn-around time necessary to the economic operation of the jet transports which were then just "around the corner", the trend in facilities arrangements was firming rapidly toward provision of as many passenger service elements as possible in close proximity to the aircraft in order that the aircraft could be unloaded, serviced and re-loaded with the least delay. This meant finding room for departure rooms wherein the passenger is processed immediately prior to boarding, public lounge space, toilets and, because the bulk of the people are there, food and bar concessions, news and gift stands, telephones and other elements, to say nothing of finding room for operational facilities for airline operators' line crews, service elements and various other operational functions. The so called "finger" scheme which is current in many of the major airports throughout the country and on which the layout was at that time premised, began to bulge at the seams. The length of fingers needed to accommodate 65 to 70 gate positions on the apron was, by virtue of the limiting geometry of runway and taxiway commitments to the north and south, literally squeezing the parking lot in the center down in size below an acceptable minimum. The fingers themselves, because of their corridor-like proportions did not afford the necessary enclosed area in which to accommodate all the requirements

which were then building up. In addition, the parallel lines of fingers, 1000 to 1200 feet long, were inhibiting the free and unobstructed flow of aircraft to and from the gate positions. Going back to the volumes of studies and sketches accumulated over the years it was decided that a way must be found to provide a decentralized lounge and departure facilities as close to the aircraft as possible and yet maintain the close proximity to parking lot of the initial contact of the passenger with the airline ticket and check-in counters. It would then be possible to enlarge the parking area, provide passenger and operational facilities where they were needed, close to the parked aircraft, free up the circulation on the apron and still provide a check-in counter and ticketing facilities as a way-station enroute to the aircraft.

In order to provide a level access for the walking passenger, the parking lot was depressed one full level (14 feet) below the general level of the parking aprons and access channels for both passengers and baggage were developed under the apron to the basement or channel level of the passenger facility which soon became known as the satellite. Escalators lift the passenger through two levels to the public lounge and departure areas thirteen feet above the apron level. The size, shape and location of these satellites in the parking aprons were developed from, again, the geometry of the site. Numerous studies were made and discussed with airlines representatives, Department Staff and others concerned to determine the optimum number of positions per group. Studies with 5, 6, 10, 12 and more were laid out on the basis of turning circle geometry, building area requirements and site dimensional limitations. The grouping that was finally approved provided, for the ultimate development of the project, 7 Satellite groups of 10 jet aircraft of the 707 or DC-8 class in each group. A small rectangular space developed at the east end of the south apron provided 4 more jet positions for a total capacity of 74 gates. In the transitional years while piston engine aircraft are still in use in some numbers, even more parking positions may be developed. The 10 gate position group was settled on, among other reasons, because the geometry again provided ample space in the interior of the group for the development of passenger and operational facilities on two main levels in the amount of approximately 80,000 square feet per Satellite. Needless to say this area was quickly spoken for by the airline operators, concessionaires and the City. Future expansion beyond the limits of present area requirements and fund availability is provided for internally by means of structural accommodation for future mezzanine levels and by taking over some inner courts now unoccupied.

Ticketing and baggage claim services are provided in 60 foot wide buildings flanking the parking lot at the inner edge of the north and south aprons. These buildings are currently planned as one and two story buildings stressed for addition of a third story if required. They vary in length according to the requirement of the airline tenant. These buildings, although spacious, provide no lounge areas, waiting rooms, or major concession areas. Additional office areas for tenants are provided on the second floor at apron level.

Expeditious handling of passenger baggage, mail, top off cargo and other express is second in importance only to the prompt servicing of the passengers' needs. Because of the 360 degree accessibility of the Satellite to arriving and departing aircraft on the apron, no exclusive avenue of approach to the Satellite is available for ground transportation. This resulted in an early decision to limit vehicular transportation on the apron to the practical minimum. In order to accomplish this several planning problems had to be met, e.g. aircraft fueling. Because of the high volumes of fuel to be handled all airline

tenants are now planning to install some form of underground fueling at each gate position. Other support utilities such as; ground starting power, compressed air, domestic water, power for air conditioning and many other uses are being made available.

Baggage handling and transportation being the other main source of apron traffic, the need to provide some avenue of access other than the apron surface was of the utmost importance. This was solved by the provision of separate access channels for baggage only, connecting the Satellite and Ticketing buildings under the apron level. Each airline tenant was then afforded the opportunity of determining the baggage handling method best suited to its individual operational characteristics and economics. Some plan to install completely automatic hi-speed conveyor systems with electronic sorting and handling devices; some are developing normal conveyor systems of less sophisticated nature; some are planning mechanized systems of the tow-veyor type and others will no doubt continue to use the conventional baggage cart train. These baggage channels are being developed to accommodate this full variety of schemes. The outbound channel leads from the ticketing and check-in area, under the apron and ramps up to apron level at the Satellite. Here the baggage will be sorted, put on cart trains or in unit baggage containers and carried over the apron to the aircraft. Inbound baggage follows the reverse course through its own separate channel to the baggage claim area of the Ticketing Building where the passenger claims it and steps out on the sidewalk to pick up his ground transportation. The passenger channels have been so designed that should moving sidewalks become desirable they can be installed at a later date.

Thus, the basic problem of getting the passenger and his baggage to the aircraft is almost completed. The passenger arrives in the public lounge area of the Satellite Building, each about 150 by 320 feet over-all in size, where he has full access to a restaurant coffee shop or snack bar, a bar and cocktail lounge, gift shop and newstands. Airlines' passenger service personnel are available to answer questions and give directions, and below at apron level, all the operational facilities needed to service the aircraft and handle the passengers baggage are available. To further ease the passenger's trip to the aircraft, provision is being made to accommodate various types of fixed and mobile bridges or enclosed gangplanks which will deliver the passenger directly from the lounge area to the interior of the aircraft under shelter or completely enclosed from noise and the weather. Where these facilities are not being developed by the airline tenant, escalators and ramps will provide easy access to and from the apron level for normal passenger loading. It is expected that ultimately the second level loading device will find general acceptance. The Satellite design has been developed to accept the many various devices now being developed.

One of the conditions of the jet age airport about which much has been said and studied and yet about which not enough experience has actually been accumulated is noise. Los Angeles in general and the airport in particular is fortunate in having been exposed to this problem for some years. As a result of this, the activity of jet aircraft around the new terminal facilities will not bring, in our opinion, many surprises. Boeing and the other airframe manufacturers have developed noise suppressors as an integral part of the jet engine. With these suppressors in use jet aircraft have been moving in and out of Los Angeles International without most of the people in the City or even on the airport ever being aware of their presence because of sound. The Joint

Venture engaged in considerable study, with acoustical engineers with respect to this problem as it bears on architectural design and detailing. It was concluded that the economics of the situation prevent achievement of such sound reductions as one might find in full double glazing throughout the Satellite Building. Normal building construction will achieve a high percentage of the theoretically desirable sound reduction at a fraction of the cost necessary to achieve the higher sound losses. As a result attempt has been made to use positive closures, carefully placed baffles and good normal construction with interior acoustical treatment to achieve the necessary control of sound.

The planning to this point has been directed at getting the aircraft out of the air and to the gate position; the passenger and his bags from his car or bus to the aircraft while providing all the services he normally has time to utilize. For the passenger who has more time to spend at the airport, or for the family or friends who occasionally must wait for a delayed arrival, planning has provided for the development of various service and commercial facilities to be situated on an elevated plaza above the parking lot. Present planning calls for the development of a structure which will include a high level restaurant and bar with an observation deck above; the central commissary kitchen for the food concessionaire; an employees cafeteria and various other services such as barber shop, beauty parlor, Post Office, bank, valet, toilets and dressing rooms, as well as such other elements as may become desirable as the need develops. Also included in the center development will be a central utility plant providing heating and cooling water for the terminal development and a services and shops element in which will be developed the required police and emergency medical facilities, maintenance crew offices, lockers, etc., and primary power vaults and telephone equipment vaults. A twelve story tower with control cab on top will house FAA control personnel, radar and communications gear, and offices. The Department of Airports staff offices have been developed in a raised, one level element surrounding the Tower. This building group also serves to mark the main entrance to the terminal area.

Internal circulation is provided by means of a peripheral road system surrounding the parking lot and providing direct access to the Ticketing Buildings. A circulating type of internal transportation system is being developed to accommodate interline transfers from one side of the terminal area to the other and to provide transportation for the passenger who occasionally may find himself obliged to park some distance from his destination. A series of secondary passenger channels are to be constructed under the south apron linking these four principal Satellites in order to provide for interline transfers.

International traffic, although expected to develop rapidly in the near future, now represents a relatively small percentage of the total traffic to be handled. Thus it became apparent that utilization of a modified Satellite group led to the most economically feasible solution. Federal clearance facilities including Customs, Immigration and Public Health and Agriculture are being developed as an integral part of the Satellite, utilizing escalators and high speed elevators to move the passenger through the various levels of the clearance process. Customs processing will be handled by means of the recently developed supermarket scheme now in use at New York's Idlewild Airport. The International Satellite will also be utilized for departures for foreign flag carriers, as well as United States carriers in overseas or foreign operations. Because of the multiple use and multiple occupancy (by several airlines) of

this Satellite-Ticketing groups, baggage handling becomes more complex than in a group exclusively occupied by one airline. Customs cleared baggage will be released to the passenger at the public level of the Satellite to be transported to the street by porter or passenger propelled carts. Departing baggage will be handled by each airline in conventional cart trains while arriving non-clearance baggage will be brought to baggage claim in a similar manner. Other schemes which were recommended included a joint-use tow-veyor with individually owned and controlled bag carts and a service corporation owned-and-operated conventional conveyor system. Individual economic problems of the various airlines involved prevented the further development of these ideas at this time.

Other problems in which the planning group has a vital interest at Los Angeles International are the ingress-egress from the terminal area and its relationship to the surrounding community and to the principal means of transport in Los Angeles, the freeway system. It is expected that in the near future an elevated freeway link above Century Boulevard will connect the terminal entrance with the San Diego Freeway now being developed to the east of the airport boundaries and will continue eastward to the Harbor and Santa Ana Freeways, thus giving rapid access to all parts of the City and its metropolitan area. Although these problems are beyond the scope and program of the airport development they are nonetheless vital to the best functioning of the terminal area.

Future planning for the airport includes development of the present terminal area as an air cargo terminal, additional maintenance area development to the west and possible development of take-off runways to a practical maximum of 14,000 feet if this becomes a requirement.

Fortunately the planning of the Los Angeles International Airport terminal facilities and airfield improvements has been developed in an atmosphere of full participation by all agencies and operators directly concerned with the outcome of the development. While this condition contributes an untold number of complexities to the planning process and at times seems endless, it is felt that the end result will be far superior in functional and economic excellence than a unilaterally designed project. That it will be a new and exciting experience for the air traveler is an approaching certainty with one new runway nearing completion, and the Control Tower and Administration facilities now under construction; with additional increments of civil engineering work, utilities and building construction well along in the working drawing stage and scheduled to be bid early this year. The target data for completion of this $46,000,000 project is the first quarter of 1961.

The Joint Venture as architects and planners for the airport have enjoyed the rare opportunity of full range participation in development of the project from inception through the schematic stage and the hard realities of practical planning and good design to the expected culmination in a first rate airport for the jet age.

Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

CONSTRUCTION OF A PRESTRESSED CONCRETE TEST PAVEMENT

Carl F. Renz,[1] F. ASCE

ABSTRACT

The construction of a full scale prestressed concrete pavement which is to be subjected to controlled traffic testing is described. The pavement was post-tensioned, using high tensile strength steel bars encased in steel tubing and grouted. The method of partially tensioning the tendons to insure proper alignment during concrete placement is outlined as is also the method used to complete the tensioning of the tendons.

In January 1958 the U. S. Army Corps of Engineers completed construction of a prestressed concrete test pavement 500-feet long by 51-feet wide by 9-inches thick. The test pavement is located at the Sharonville General Services Depot near Cincinnati, Ohio, which is the site of the Corps of Engineers Rigid Pavement Laboratory's full-scale pavement test area. This area is utilized for simulated aircraft traffic loading tests of full-scale pavements. The information obtained from such tests is correlated with other studies for the development of design and construction criteria for military airfield pavements.

The purpose of the prestressed concrete test pavement was twofold, first, to obtain experience in this type of construction, and second, to observe the behavior of the pavement under the traffic of a specially constructed twin-tandem wheel gear test rig loaded up to 325,000 pounds.

A number of prestressed concrete airfield pavements have been built in other countries(1) and several prestressed concrete test sections have been built in this country.(2) However, none of these pavements, to our knowledge, have been subjected to controlled repetitions of traffic loading. Testing with repetitive traffic loading is necessary to evaluate the effect of fatigue so that

Note: Discussion open until March 1, 1959. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 2192 is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 85, No. AT 4, October, 1959.

1. Chf., Structural Branch, Ohio River Div. Labs., U. S. A. Corps of Engrs., Cincinnati, Ohio.

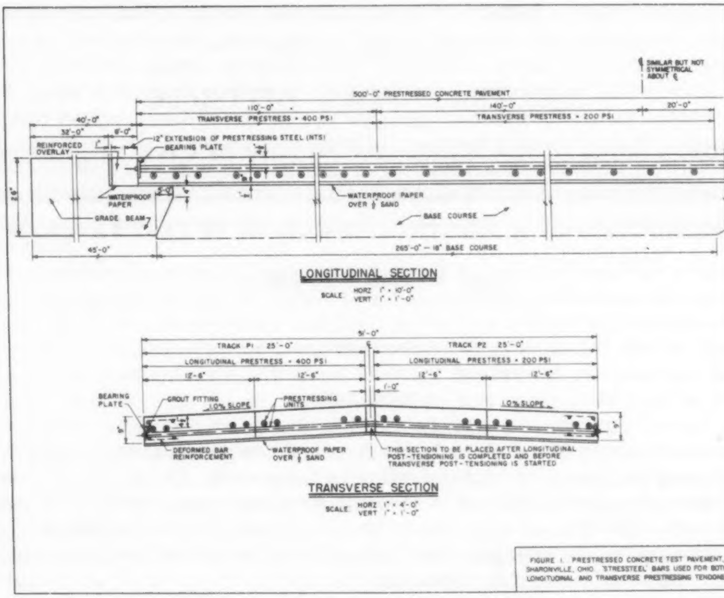


Fig. 1. Half longitudinal and full transverse sections of prestressed concrete test pavement.

reasonably accurate predictions can be made of the life of the pavement under design loadings.

A number of variables were incorporated in the design of the prestressed test pavement at Sharonville. These variables involved base treatment, levels of prestress, and types of longitudinal construction joint. Normal pavement construction practices were used in the preparation of the subgrade and bases, and for the concrete placement. The test pavement consisted of two tracks, P-1 and P-2, separated by a one-foot wide center strip of concrete, as shown on the transverse section of Fig. 1. Each track was composed of two 12.5-foot wide lanes which provided for a longitudinal construction joint in each track. The concrete in the pavement was placed in the four 12.5-foot wide longitudinal lanes in the sequence Lane 1, Lane 3, Lane 2, Lane 4, as indicated in Fig. 4a. The longitudinal prestress in Track P-1 was 400 psi and in Track P-2, 200 psi. Two levels of transverse prestressing, 200 psi and 400 psi, were used across the full width of the two test tracks. Both longitudinal and transverse prestressing were accomplished by post-tensioning. The sequence for the application of the prestress was as follows: both Track P-1 and Track P-2 were prestressed longitudinally; the concrete in the one-foot wide opening between the two tracks was then placed and allowed to harden; and finally the transverse prestressing was applied. After all prestressing had been applied, the conduits containing the prestressing steel were grouted.

At the south end of the pavement, which is clearly visible in the foreground of Fig. 4a, a 26-inch thick plain concrete maneuver area for the traffic rig

and the grade beam was provided. Similar construction was at the north end of the pavement. These details are shown in the longitudinal section of Fig. 1.

Subgrade and Base

After making the normal provisions for surface drainage and ground water control, the top 6 inches of the fat clay subgrade was compacted to 95 per cent of its Modified AASHO maximum dry weight at the appropriate water content. Both sheeps-foot and steel-wheeled rollers were used. The subgrade was then covered with a graded natural sand and gravel base course compacted to better than 100 per cent of its Modified AASHO dry density using rubber-tired and steel-wheeled rollers. Two thicknesses of base course were used, eighteen inches under the south half of the test pavement and four inches under the north half. Final measurements of the subgrade modulus indicated a "k" value of 70 psi/inch for the 18-inch base and 60 psi/inch for the 4-inch base. Actually these values were only a slight improvement over the modulus of the fat clay subgrade. After setting the steel forms and completing the fine grading, a 1/2-inch thick layer of graded sand was placed between the forms and covered with water-proofed reinforced kraft paper. This sand layer was provided to reduce the friction between the base of the pavement and the foundation. Previous small-scale tests indicated that a sand layer would provide a coefficient of friction in the order of 0.75 between the pavement and the base.

Stressing Steel

The contractor elected to use STRESSTEEL rods for both the longitudinal and transverse prestress tendons, although the specifications permitted other types such as wires or strand. The longitudinal rods were encased in flexible steel tubing and the transverse rods in rigid steel tubing. The rigid tubing provided added support for the longitudinal steel tubing which was laid on the transverse conduits. For the longitudinal STRESSTEEL rods, a threaded coupling was required every 67 to 81 feet, as these were the limiting lengths of rod the manufacturer could provide. Fig. 2a shows the enlarged conduit at the couplings and the transverse conduits supported on wire chairs. Also shown is the doweled and keyed construction joint treatment between two 12.5-foot wide lanes. The other type of longitudinal joint treatment, not shown, was the plain butt joint.

To obtain the required levels of prestress (200 and 400 psi) in the 9-inch thick pavement, two sizes of STRESSTEEL rods were selected. These rods were 7/8 inch and 1-1/8 inches in diameter and had a minimum ultimate tensile strength of 147,000 psi. Table 1 gives the size and spacing of these tendons for the two levels of longitudinal and transverse prestress. The variation in the spacing for the same level of prestress in the longitudinal and transverse directions was made to compensate for the difference in the stress losses in the steel caused by friction between the tubes and the rods. In all cases the tubing was 1/4 inch larger in diameter than the tendon. At the couplers in the longitudinal tendons 2-1/2-inch diameter rigid sheaths were used. These sheaths were a minimum of 1/2 inch longer than the distance the coupler moved during the stressing operation. The sheath length varied from 18 to 28 inches depending on the location along the length of the pavement.

Along the outer edges and at the ends of the pavement, steel bearing plates to jack against when the prestress was applied were set in the concrete at

a. Tendon spacing and longitudinal joint detail.

b. Bearing plate and grout fitting detail.

Fig. 2

Fig. 2a. Tendon spacing and doweled and keyed longitudinal joint detail.

each tendon. These bearing plates were placed inside of and fastened to the forms. The dimensions of the plates were such that the average compressive

Table 1

Size and Spacing of Prestressed Tendons

Direction of Rod	Concrete Prestress, (psi)	Diameter of Rod, (inches)	Spacing of Rod, (inches)
Longitudinal (Track P-1)	400	1-1/8	18-3/4
Longitudinal (Track P-2)	200	7/8	25
Transverse	400	1-1/8	22-3/8
Transverse	200	7/8	27
Transverse	0	No. 6*	9

*No. 6 deformed reinforcing bars.

Fig. 2b. End bearing plate and grout fitting detail.

stress on the concrete would not exceed 0.6 times the compressive strength of the concrete at the time of stressing. The rods were drawn through conical holes in the bearing plates and were anchored by means of truncated-cone shaped wedges. A short pipe nipple was welded to each bearing plate at the narrow end of the conical hole. The nipple formed the outer edge support for the tubes encasing the tendons. Attached to the nipple on the bearing plates was a grout fitting which extended out of the face of the edge of the pavement to provide access for the grout after post-tensioning the bars. Fig. 2b shows a detail of the bearing plate and fittings.

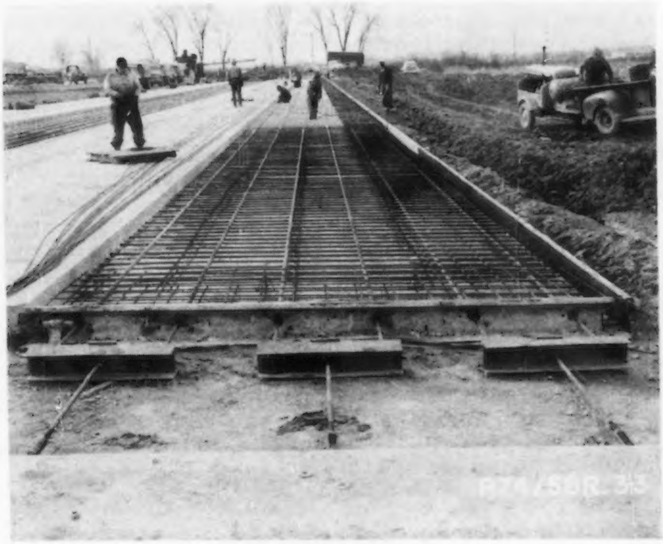
Steel Placement

After the forms were set and prior to placing the steel, holes were burned in the inside pavement forms to accommodate the transverse tubes. The transverse tubes were set in place and supported on wire chairs having a metal base to prevent puncturing the paper layer.

The longitudinal bars were threaded through the flexible tubing and the coupler sheaths prior to supporting them on the transverse tubes. The various lengths of bars were coupled together and the flexible tubing connected to the coupler sheaths.

To align the bars properly and hold the alignment during concrete operations, as well as to reduce the wobble in the tubing, all longitudinal bars were tensioned to 10,000 psi and held in this position until the concrete had been placed and hardened. Fig. 2a illustrates the details of the spacing of the tendons and the couplers and Fig. 3a the method of the preliminary tensioning the bars.

During the concrete placement, the transverse bars were inserted in the rigid tubes to give added support for the longitudinal tendons. After the concrete had hardened, the rods were removed and replaced when the next 12.5-foot lane was ready for concrete placement.



a. Pretensioning tendons.

b. Equipment for stressing tendons.

Fig. 3

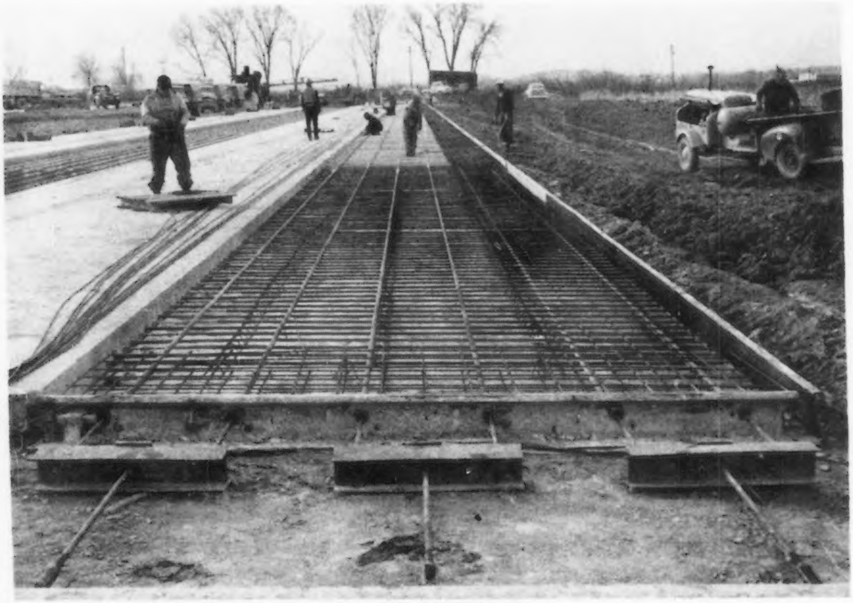


Fig. 3a. Pretensioning longitudinal tendons in Lane 1.

In addition to the prestressing steel, it was found advisable to add deformed bar reinforcement along the outer edge of the two outer lanes, Nos. 1 and 4, and at each end of each lane. This reinforcement was in the form of "U" shaped No. 3 bars placed perpendicular to and behind the bearing plates and extending four feet into the pavement. In addition to the "U" bars, five rows of straight No. 3 bars were placed along the top and bottom of the outer edges of the two tracks and were fastened to the "U" bars.

The north seventy feet of both tracks were not prestressed transversely but were reinforced with No. 6 deformed bars. These bars were placed in a single layer directly below the longitudinal tendons and were fastened to them. The reinforcing was continuous across the longitudinal joints as splices, where necessary, were made in the interior of a lane.

Concrete Placement

The first concrete placed for the project was in the grade beams at each end of the pavement (see Fig. 1). Each of the two beams were placed in four lanes, the outer lanes being 12.5-feet wide and the inner lanes, 13-feet wide. The joints were doweled. The top surface of that portion of the grade beams which extended under the 8-foot long reinforced overlay slab at each end of the tracks and the first 10 feet of the prestressed pavement proper, was given a smooth steel trowel finish to reduce the friction between the 9-inch pavement and the grade beam. To facilitate construction, the sand layer was eliminated under the overlay slabs, only a bond breaking layer of waterproofed paper being used at this point.

The concrete for the grade beams had a cement factor of 5.5 sacks per cubic yard and a water-cement ratio of 0.42 by weight. The aggregate

consisted of 30 per cent natural sand and 70 per cent 1-1/2-inch maximum size crushed gravel. The average slump was 2 inches and the air content was 5 per cent. The average 28-day compressive strength was 4200 psi.

The concrete in the pavement was placed in four lanes, each 12.5-feet wide. A one-foot center strip was placed between Lanes 2 and 3 after the longitudinal tensioning was completed. The order of placing the concrete was Lanes 1, 3, 2 and 4. Due to the possible damage internal vibrators might do to the extensive instrumentation and to the tubing, it was felt that the use of surface type vibrators would be preferable for general use. The use of internal vibrators was therefore limited to the sides and ends to insure good placement of the concrete around all bearing plates and deformed bars along the edges of the pavement.

The concrete used in the pavement had a cement factor of 6.0 sacks per cubic yard and a water-cement ratio of 0.44 by weight. The aggregate consisted of 37 per cent natural sand and 63 per cent 1-inch maximum size crushed gravel. The average slump for the four lanes was 2 inches and the average air content was within the 5 per cent range. The 28-day compressive strength of field cured cylinders varied from 4800 to 5000 psi for the four lanes. Corresponding standard-cured specimens varied from 5700 to 6200 psi for compressive strength and from 700 to 800 psi for flexural strength at 28 days.

The surface vibrator used for Lane 1 did not function satisfactorily and it is believed that its action was ineffective. The type of vibrator used for the other three lanes was suspended from leaf springs and appeared to be much more effective, although cores taken from the finished pavement indicated that there was some minor honeycombing. For future pavements internal vibrators and proper care to insure against injury of the tubes encasing the tendons or of the imbedded instruments will be recommended.

The concrete was placed during November and December 1957. When necessary to insure curing temperature above 50 degrees during the first 72 hours, the water and aggregate were heated prior to mixing. The completed slabs were covered with polyethylene sheeting and straw to insure proper curing temperatures.

Post-Tensioning the Tendons

The preliminary tensioning stress of 10,000 psi in the longitudinal tendons, as previously cited, was maintained until the concrete had hardened. The day after placement, this load was released and the tendons were pulled back and forth through the tubes to insure their being free. The bars were then set so that the couplers were located properly in the sheaths to allow full tensioning of the rods.

Within 24 to 72 hours after the concrete in each lane had been placed, the longitudinal tendons were given a preliminary tensioning to aid in preventing shrinkage cracking. The amount of prestress in the concrete and time of application was dependent on the early concrete strength and temperature and varied from 75 to 100 psi for the several lanes. Whether this initial prestressing was a factor in controlling the shrinkage cracking was not definitely established as the temperature variation during the first few days after each placement was relatively small. It is believed, however, that when wide variations in temperature occur during the early curing period, such initial prestressing may be important.

Fig. 3b. Equipment used for stressing tendons.

The above preliminary tensioning, as well as the final post-tensioning, was accomplished by means of 60-ton hydraulic jacks operated with an electric pump. Smaller 30-ton hand-operated jacks were used to seat the cone shaped anchors in the sockets in the bearing plates. The equipment used for stressing the tendons is shown in Fig. 3b.

The amount of force introduced into each bar was checked by gages on the hydraulic jacks and by the measured elongation of the bars. These measurements were checked with extreme care to insure the proper tensioning force.

During the final post-tensioning operation check tests were made to determine the amount of friction between the tubes and the tendons. These tests indicated that, for the longitudinal tendons, a stress of 0.72 times the ultimate strength of the steel was required to overcome the friction between the steel bars and the tubes. After holding the stress at this level for two minutes the load was reduced to and anchored at a stress of 0.6 times the ultimate. The longitudinal stress attained in the two tracks is tabulated in Table 2.

After the final post-tensioning of the longitudinal steel in both tracks had been completed, the one-foot gap between the two tracks was filled with high-early strength cement concrete. As soon as this concrete had attained sufficient strength, the transverse post-tensioning of both tracks was completed. This operation followed the same procedure as with the longitudinal bars, except that the bars were anchored at 0.7 times the ultimate strength of the steel. The temporary loading to overcome friction was to 0.8 times the ultimate strength of steel. The transverse stress attained in the two tracks is also tabulated in Table 2.

The post-tensioning of both test tracks was accomplished with only one untoward incident. After completing the full tensioning of fourteen of the sixteen longitudinal tendons in Track P1, and during the tensioning of tendon 16, the concrete at the bearing plate for this tendon failed, causing a sudden partial release of the tension in this tendon. Within a few minutes a similar failure occurred at the adjacent fully tensioned tendon 15. The resulting area of crushed concrete was approximately nine square feet. Field-cured test specimens indicated adequate strength for the concrete near the failure point; however, since tests of cores taken adjacent to the crushed area indicated a strength only one-third as great as the field-cured test specimens, the failure was attributed to weak concrete. This experience points up the importance of taking test specimens of the concrete placed directly at the bearing plates, not several batches later, as in the present instance. The tension remaining in tendons 15 and 16 was released from the opposite end of the track, and the tension in the four adjacent tendons was fully or partially released. The concrete in the affected area was removed; tendons 15 and 16, which had been slightly bent, were straightened and reset; the reinforcing bars were straightened or replaced, as needed; and extra reinforcing bars were added behind the bearing plates. Hi-early-cement concrete was used to repair the area and, after proper curing, the post-tensioning of all bars in the track was completed without further incident.

This 'successful' failure indicates that exceptional care should be exercised in obtaining the true strength of the concrete at the bearing plates, in order that the post-tensioning is not begun before that concrete has attained sufficient strength.

Table 2

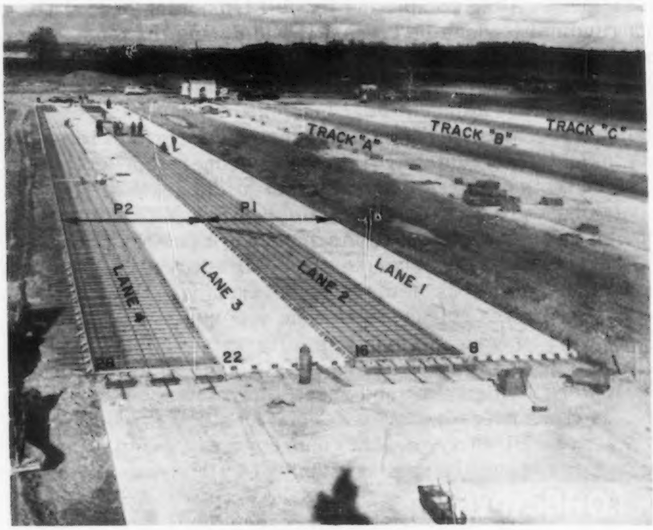
Stress in Tendons and Concrete

	Track No. P-1			Track No. P-2		
	Longitudinal	Transverse		Longitudinal	Transverse	
		South End	South Quarter		North Quarter	North End
Stress in steel at anchorage, ksi	88.2	102.9	102.9	88.2	102.9	(1)
Stress in steel after losses, ksi	72.0	81.9	85.0	75.1	81.9	(1)
Final prestress in concrete, psi	400.	400	200.	200	400.	(1)

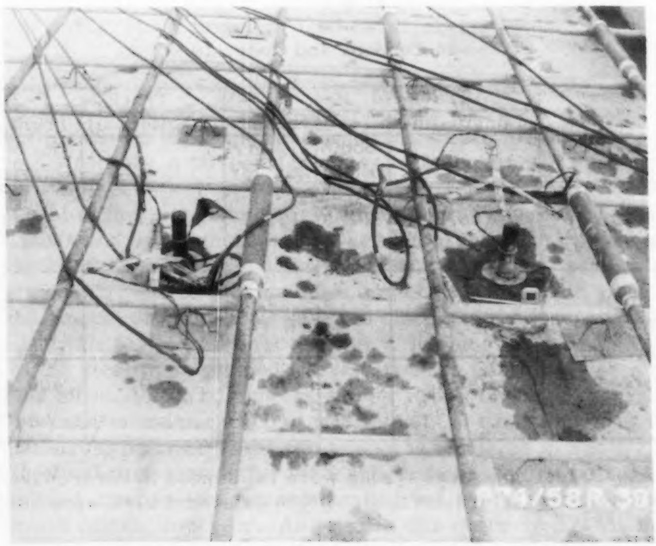
(1) The north 70 feet of the two tracks were reinforced in the transverse direction instead of prestressed. No. 6 deformed bars were used.

Grouting

Upon completion of the final post-tensioning, the tubes encasing all tendons were filled with neat cement grout. The original plan was to grout the full 500-foot length of the pavement without relief holes. However, relief holes had



a. Aerial view of partially completed test tracks.



b. Instrumentation in tracks.

Fig. 4

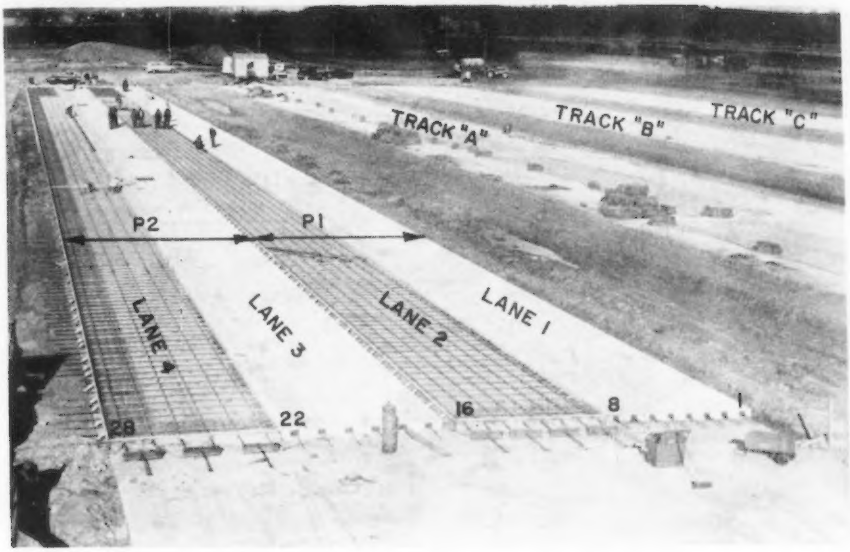


Fig. 4a. Aerial view of partially completed test tracks.

to be drilled into the coupler sheaths near the mid-point and quarter-points of the pavement in order to fill the tubes successfully. The water content of the grout varied from 4.5 to 6.5 gallons per sack of cement. An admixture was used to increase fluidity and retard set; but little evidence was noted that its use improved the grouting operation. A maximum pressure of 150 psi was used to pump the grout.

The final two operations to complete the pavement were to place the reinforced overlays at the ends of the pavement and install the expansion joints. The overlay sections, 9-inches thick and 8-feet long, were placed at each end of the prestressed pavement to fill the section left open to provide space for the longitudinal post-tensioning. A layer of water-proofed paper was placed under these sections to prevent bonding to the grade beam. The longitudinal tendons which were left extending out of the prestressed section served to tie the overlay sections to the prestressed sections. Thus the full length of the 9-inch thick pavement was 516 feet.

Two types of expansion joints were used. At the north end, a one-inch thick premolded joint filler was placed between the maneuver area of the grade beam and the reinforced overlay. At the south end, a three-inch gap was left between the overlay slab and the south maneuver area. This joint was later filled with cold poured polyurethane-bitumen foam.

Instrumentation

To assist in the analysis of the results of the loading and traffic tests of the test tracks, a series of deflection and strain gages were placed in the pavement. The deflection gages were the differential transformer type

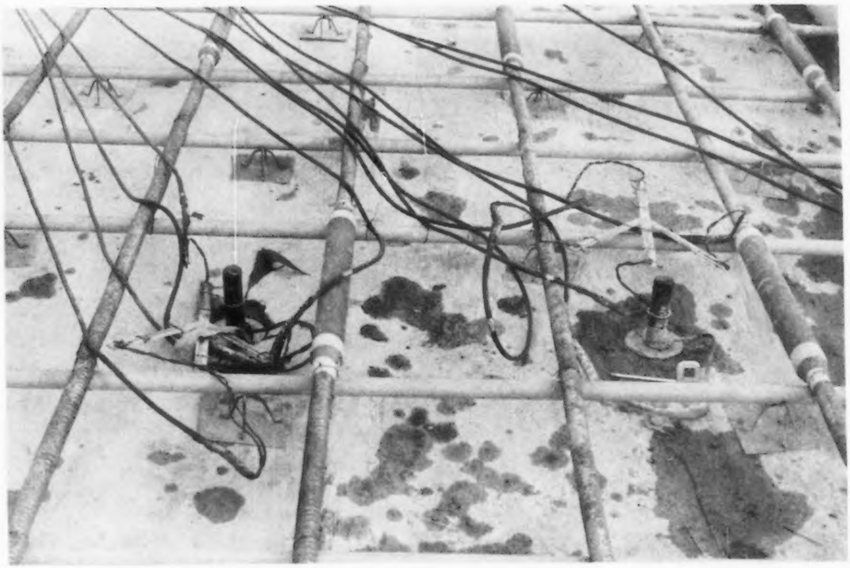


Fig. 4b. Instrumentation in interior of Lane No. 2.

developed in the Ohio River Division Laboratories. They have a range of two inches. The accuracy of the gages and the recording circuits is plus or minus two thousandths of an inch. The strain gages were the VALORE type SR-4 resistance gage. These latter gages were generally located one-eighth inch below the top surface of the pavement. Both types of gages were placed along the longitudinal joint in each of the two test tracks and at several interior locations. Fig. 4b shows these two types of gages. In addition to these gages, thermocouples were placed at four levels in the 9-inch pavement to observe temperature variations from the top to the bottom of the concrete. Reference points were located in the surface of the pavement and at each expansion joint for measuring the movement of the slab with temperature changes.

ACKNOWLEDGEMENTS

The construction of the prestressed test pavement was performed by the W. L. Harper Company of Cincinnati, Ohio. The designs, plans and specifications, and construction supervision were provided by the staff of the Ohio River Division Laboratories. This work was under the general supervision of the Airfield Branch of the Military Construction Division, Office, Chief of Engineers. The work was done under and by the authority of the Chief of Engineers, U. S. Army.

REFERENCES

1. Prestressed Concrete for Airfield Pavements, Civil Engineering, Nov. 1958.

2. Prestressed Concrete Research, Highway Research Board, Bulletin 179.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

JET AIRPORT LIGHTING REQUIREMENTS

M. A. Warskow[1]

ABSTRACT

Future developments in airport lighting will, in large part, result from its use together with electronic equipment to give better control of aircraft when airborne or on the ground. Future airport lighting fixtures will frequently be installed in heavy-duty paved surfaces and thus provision for them must be included in early phases of planning. Aids for approach, landing and ground control traffic are discussed, and the special needs for controls and circuiting are reviewed.

The planning already accomplished to bring jet aircraft into operation has made very impressive changes in airport design concepts that involve longer runways, wider taxiways, bypass areas, enlarged parking areas and other improvements to increase capacity. Greater changes are still in store to continue to accept the larger aircraft and handle them efficiently.

Likewise, the coming of jet aircraft has great meaning to the planning for new airport lighting aids that can help to increase the reliability and safety of jet operations. Reliability and safety are ever more important with the higher landing and takeoff speeds, the greater utility and cost of the aircraft, and the large passenger loads of these big aircraft.

The improvements and developments in airport lighting or visual aids to accommodate jet aircraft will, in large part, result from a closer merger of electronic equipment and visual-aid equipment. Additional electronic equipment must be developed and applied to give more precise and flexible control of aircraft in the air and on the ground and the implementation of these control functions will, in many cases, require visual aids to effect a complete system.

Jet aircraft will become the backbone of our air transport system because of the additional speed they can deliver, thus making travel more efficient.

Note: Discussion open until March 1, 1960. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 2193 is part of the copyrighted Journal of the Air Transport Division, Proceedings of the American Society of Civil Engineers, Vol. 85, No. AT 4, October, 1959.

1. Airborne Instruments Lab., Mineola, N. Y.

The entire airport concept must be designed to make it possible for jet aircraft to deliver this efficient service. The airport lighting and visual aids installed on an airport can help in a major way to make this efficient operation possible.

The greater use of visual aids required in the future will mean some basic changes in thinking on the part of airport designers, because the cost of providing these visual aids in conjunction with electronic aids will be a higher proportion of total airport cost than is the case today. The operational part of an airport is much more than pavement area. Visual aids can help to make this pavement have a much greater utilitarian value, but this will require a greater proportion of expenditure on such visual aids. In many instances, pavement design and layout must cater to the needs of visual aids to permit their optimum use.

Standard airport lighting equipment already in use will continue in use in many ways in the future. This discussion will be directed at installations and developments beyond the standards of today.

Approach and Landing

The approach and landing problem during good weather (VFR) operations is a critical operation but the assistance needed from visual aids is provided by equipment developed for low visibility (IFR) operations except the equipment may be applied on a smaller scale. Thus, the normal runway lighting in use today, supplemented by either visual glide path indicators or stub approach lights should satisfy such requirements. Standards for the application of stub approach lights are already available and consist of a shortened section of the centerline approach lighting system. Experimental work is still under way on the development of a visual glide path indicator, and whether such a device will receive general acceptance is not known at this time. However, the history of these devices shows that their usefulness is limited, and it is more likely that standard runway lighting plus stub approach lighting would be the future application on non-instrument runways.

Today in instrument approach operations (IFR), the concept is that an approach is made to a minimum altitude on instruments, at which point transition must be made to visual flight to complete the approach and landing. The lowest minimum value in effect today is 2000-foot runway visual range, no ceiling specified, which is only in use in Newark Airport. This criteria is predicated on visibility only and is an exceptionally low minimum because of the excellent combination of electronic approach aids, visual aids, and weather reporting devices in use for the instrument runway. The more common statements of minimums are the 200-foot ceiling and one-half-mile visibility, which is in use at several airports. It is probable that to lower this minimum value will require the provision of more precise and flexible electronic aids, better visual aids, and better weather reporting data.

The great need in electronic aids in this regard is for an improved glide path that will permit approach to a lower altitude and eventual flareout for all types of aircraft. Development is now under way by the Federal Aviation Agency to provide this type of facility, and planning for visual aids should envisage the successful completion of this development. The significance of such development to visual aids design is that the visual aids must have greater all-weather capability in the touchdown and rollout area.

The visual aids required for the future are an approach lighting installation probably as we already know it—the centerline system with flashing condenser discharge lights, high intensity runway edge lighting, runway painting supplemented by what have come to be known as "narrow-gauge runway and roll-out lighting"—flush lights within the runway paving. Except for the flush lights, standard equipments and installation practices are already available on approach and runway lighting and painting. However, one improvement is desirable in runway edge lighting—the use of 100-foot longitudinal spacing instead of the standard 200-foot spacing. The authorization for the exceptionally low minimums previously mentioned for Newark Airport are specifically tied to the 100-foot spacing of the runway edge lights with a higher minima required for 200-foot spacing. Thus, operational proof exists for use of the closer spacing.

The types of lighting that will fill the need for narrow gauge and roll-out installations are now being developed and evaluated. Today there are three concepts that are competing to satisfy this requirement. The one that has the greatest amount of test background application is the flush grid type lights installed within the pavement on a 60-foot gauge with the lights on 100-foot longitudinal spacing (Fig. 1). Similar lights are being used to quite a large extent in overrun approach lighting installations. An evaluation program of the grid type lights is nearly complete at Dow Air Force Base by the U. S. Air Force.

A semi-flush, prism-type unit is being evaluated to determine its merits for this same application. If this should be successful, it would be less expensive and difficult to install. However, it has disadvantages in connection with snow removal, the "bump" it creates, and possibly from a functional standpoint in that it provides only a point source of light as contrasted to the grid type which, in addition to the point source, has a lighted grid area which seems to have some value for night depth perception.

A different concept for solution to the touchdown problem is one involving the use of closely-spaced but low intensity lights which will utilize greater numbers of units having less penetrating power to provide the pattern needed to give depth perception for touchdown. This concept has been developed by the University of California and is being explored under contract to the Federal Aviation Agency. A big advantage of these units is their simplicity and thus economy with the added feature that if experience shows a configuration change is needed, little effort would be required to rebuild the narrow gauge system to another configuration with this type of unit. The biggest problems are getting adequate intensity to be useful in the daylight fog condition, which is the most severe condition to meet, and providing a unit with physical characteristics adequate to withstand snow removal operations.

Another technique for lighting the touchdown area is that of installing fluorescent floodlighting along the edges of the runway in the touchdown area. The Federal Aviation Agency has an experimental installation underoing evaluation at Washington National Airport. This floodlighting can at best provide only a low intensity light at the center of the runway and thus can only be helpful in night-time low visibility conditions as the intensity is inadequate for daytime use.

The provision of approach lights and narrow gauge lights should accommodate the actual touchdown, and centerline runway lights should then be provided for the roll-out phase of the landing. These can be the same type of fixture used in the narrow gauge installation. Any of the installations that are made

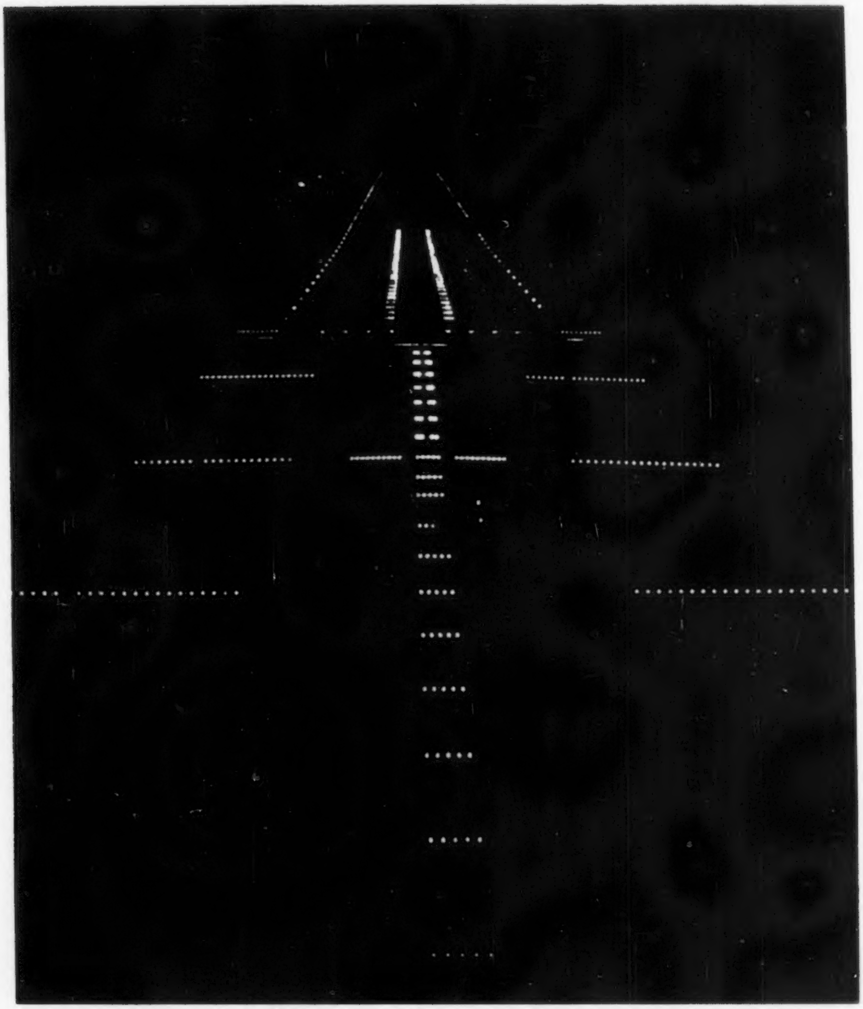


Fig. 1. Night View of Approach and Runway Lights Showing Narrow Gauge Lights within Runway.

for these uses must provide for all-weather, day and night operation, and be equipped to melt snow in areas where this is a problem.

Until the results of the several evaluation and development programs are available, designers will have difficulty determining the proper application. However, enough has been accomplished to assure the airport designer that he must provide for improved lighting of the touchdown area at airports where bad weather is common and reliable operations are to be conducted.

To obtain high capacity on our major runways, high-speed taxiway exits will be provided. To make the maximum use of these exits it is necessary that marking be given very precise and adequate treatment, for the point of turn into the exit may be 600 feet away from the actual exit from the runway. Development work on this has been performed by the University of California under contract to the Federal Aviation Agency and still further work remains to be done. The marking required is a combination of lights on the surface of the runway, markings at the edge of the runway, and lights on the centerline of the high-speed turnoff. Fig. 2 indicates a configuration that appeared very promising in tests conducted by the University of California under contract to the Federal Aviation Agency. These tests utilized low-intensity, semi-flush units at spacings of 20 feet along the runway and 10 feet on the taxiway to give the clear delineation shown in this photograph. The intensity requirement for this application is much less severe than that in the narrow gauge application because the viewing speed is about 60 miles per hour when in taxi configuration. Thus visibility need not be provided for such a great distance ahead but the configuration viewed must be capable of quick and accurate interpretation.

Ground Traffic Control

The marking of taxiways with such lighting as is conventional at airports today should continue except that it may become practical to mark taxiway centerlines instead of edges as pavement widths increase, height restrictions become more severe and improved types of flugh lights become available. Improved lighting units offering considerable promise for edge lighting are under development by the Port of New York Authority, and are shown in Fig. 3.

A field largely unexplored but very necessary to efficient ground operations for jet aircraft is that of automatic control of aircraft on the taxiways and

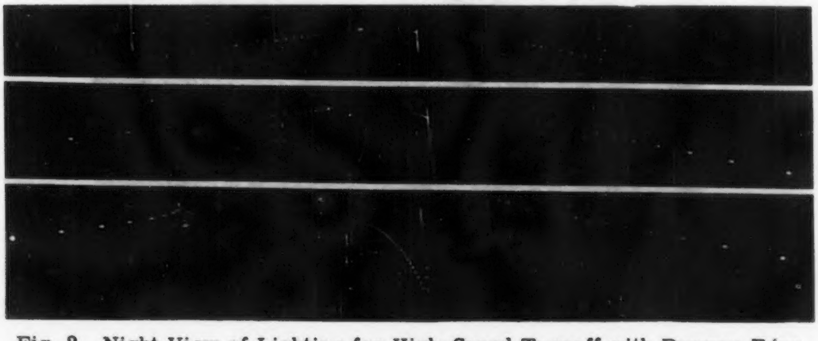


Fig. 2. Night View of Lighting for High-Speed Turnoff with Runway Edge Lights on 20-foot Spacing and Taxiway Center Line Lights on 10-foot Spacing (University of California Tests).

Fig. 3. Columnar Taxiway Lighting Installation.

during runway crossings. Work is now underway to develop a detector and display system that will indicate to the controller where aircraft are located on the airport. This can also be indicated by the Airport Surface Detection Equipment (Radar) that has a performance as indicated in Fig. 4. This is an actual picture of the airport map the radar paints, regardless of weather, on which the controller can observe all aircraft in operational areas. However, the output of either of these detection systems must be tied into a signalling system to actually control aircraft if they are to achieve maximum utilization and relieve the controller of this activity. This can be accomplished by using the detection system to make possible the application of advanced vehicular control techniques to the point where individual aircraft can be guided around

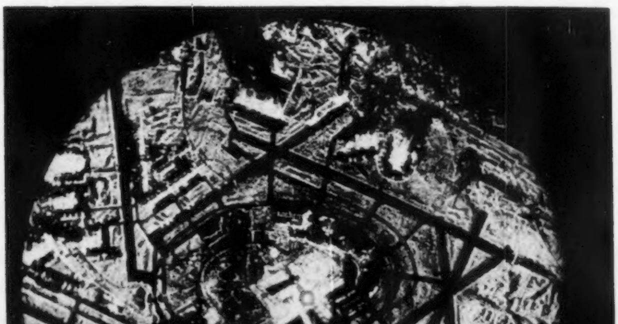


Fig. 4. Map of New York International Airport as It Is "Painted" by Airport Surface Detection Radar.

a complex airport layout without undue interference with one another and at efficient taxi speeds. In fact, where runway crossings are involved it is believed that an automatic ground traffic control system can increase both the safety and efficiency of the operation. This concept is illustrated in Fig. 5. To the pilot it would appear mainly as the application of standard vehicular control traffic lights combined with the use of signs to give instructions and locations. These visual aids can be considered all-weather at most of our nation's airports for they have the penetration and guidance needed at low taxi speeds to match the runway, approach, and landing aids.

Control Tower

These more advanced visual signalling systems with their electronic counterparts require that a more sophisticated display be given the controller at the control tower that will not only indicate the operation of lighting equipment, but indicate the status of aircraft operations on the airport. An illustration of this is given in Fig. 6. Eventually, the control of ground traffic can become entirely automatic, leaving the controller to monitor the operation.

Control and Circuiting

In order that the airport lighting aids will be more reliable and responsive to weather conditions, it is probable that extensive changes in circuiting will come into being.

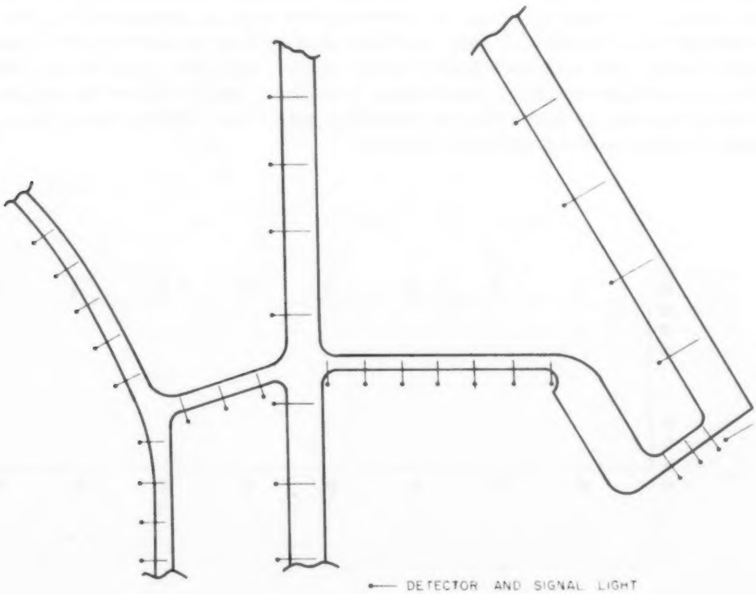


Fig. 5. Indication of Block Layout for Automatic Ground Traffic Control System.

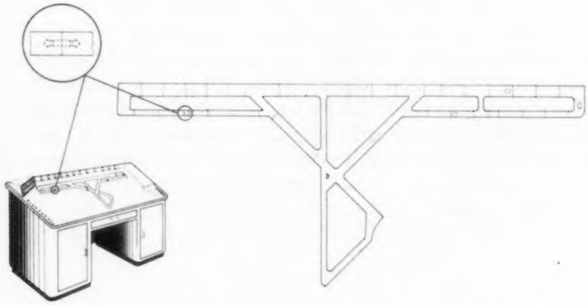


Fig. 6. Indication of Panel Required in Control Tower to Present Information on Taxiing Aircraft.

One change that is not far in the future is the use of automatic intensity control on the approach and landing airport lighting aids. These high-intensity lighting installations—the approach lights, edge runway lights and narrow gauge lights—all must be adjusted to certain weather conditions. Today this is accomplished manually by the controller according to tabulated data of weather conditions for various intensity settings. However, this could be made more responsive to the weather by interpreting the weather data being obtained in the approach zone and along that runway by the new weather-reporting equipment known as the "Transmissometer" and "Ceilometer." A large installation program is now under way for this weather-reporting equipment. These weather reporting installations eventually will be equipped with computers that will take the raw weather data as measured by this equipment and translate it into visibility and ceiling measurements (runway visual range, and approach light contact height) that are useful to the pilot. This same output could be used either to indicate to the tower the proper light intensity setting at that time, or directly control the lighting intensities, which appears to be the best ultimate solution.

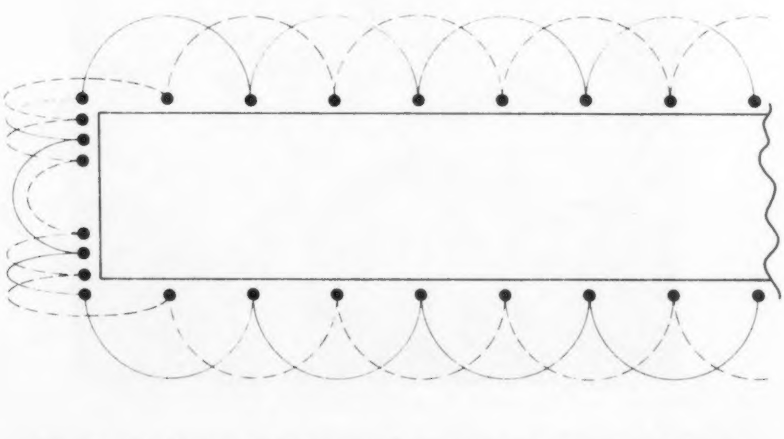


Fig. 7. Illustration of Alternate Circuiting to be Used on Runway Lighting Installations.

Modern airport lighting systems should be designed with greater thought given to reliable performance. Examples of how reliability can be improved are: (1) providing approach lights with power from dual cable systems and automatic changeovers with the dual systems connected to individual outside power sources; (2) using alternate circuiting of lights around the runway as indicated in Fig. 7. With this scheme, even with one circuit temporarily out due to trouble, half of the lights will remain in service.

At major airports, such as New York International and Newark, two complete instrument landing systems are in operation requiring two sets of airport lighting visual aids. This duplication will occur at other major airports where bi-directional approach is needed to approach all-weather capability.

The increase in both visual and electronic aids points to more widespread use of underground electrical duct systems for airport lighting cables instead of the direct earth burial application now considered standard. Provision of ducts in the original airport construction will not only make maintenance simpler, but will provide more flexibility for later changes and additions in circuiting.

CONCLUSION

In this field of airport lighting, which has seen such evolution and change, it is apparent that much more change is due. Intelligent design should accommodate these new advances in original construction plans wherever possible. Alternately, plans should be made for later addition with efficiency and minimum interruption to airport operations.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

CONTENTS

DISCUSSION

A WATER-BORNE RUNWAY[a]

Closure by David Williams

DAVID WILLIAMS.[1]—The writer is disappointed and surprised at the somewhat unimaginative character of some of the comments made by contributors to the discussion. The impression one gets is that the commentators have no real interest in any radical departure from conventional practice. They have looked at the scheme and they are struck, not by its potentialities, but by a host of minor problems of construction. And, because the solutions to those problems are not immediately obvious, they conclude that the whole scheme is unworkable. A novel scheme and a laudable effort at breaking new ground, they imply, but not a practical proposition because it is likely to be more expensive, to take longer to construct and to be more difficult to maintain than the current type of construction.

Before discussing the contributors' comments in detail, it would be worthwhile if there were first made some observations on certain aspects of the scheme:

(a) In the model tests two factors operated to produce excessive deflections under load. They are

(i) The fact that the shear joints connecting the slabs together resulted in an articulated structure.

(ii) With the square type of slab used in the tests this articulation became fully efficient when the slabs were unstaggered (Fig. 2) and semi-effective when staggered in one direction (Fig. 3).

(b) The proposed full-scale runway from the point of view of stiffness and strength.

A scheme for building a full-scale runway that has considerable attractions is that mentioned on page 11 in which the whole runway is made up of (effectively) monolithic carpets of concrete 150 ft. wide (or whatever the width of the runway may be) and 300 to 500 ft. long. Each is separated from its neighbour by a strip 5 ft. wide (supported by the same hydrostatic pressure) running right across the runway and designed to accommodate temperature variations. These monolithic stretches of carpet may be constructed by the method described by Morice and Cowley in the appendix (and Fig. 17) which facilitates the removal of individual slabs for inspection or replacement. Alternatively each monolithic area of carpet may achieve its monolithic character as a result of post-tensioning by wires stretching right across and

a. Proc. Paper 1658, June, 1958, by David Williams.

1. Research Engr., Royal Aircraft Establishment, Farnborough, United Kingdom.

along each such stretch. In either case the result is to make each carpet area a continuous slab without discontinuities either of shear or bending stiffness.

The stresses and deflections of such a slab are determined by the area of the individual water bags, since this determines the supporting pressure.

(c) Size of slab elements forming the carpet

It follows that, for such a constructional method as that described in (b), the size of an individual precast slab is at choice. The largest size consistent with ease of handling and transportation will naturally be chosen.

(d) Deflection of full scale runway under load

The problem of local gradients of the carpet under wheel loads disappears for such a scheme as that above described because, not only will the deflections themselves be small under the wheel, but they will be constant as it rolls along.

(e) Effect of sloping ground

Regarding the effect of ground gradient in setting up a sliding force on the slab down the gradient, it is important to notice the smallness of this force. A monolithic slab 150 ft by 400 ft by 8 in. weighs about 5.5×10^6 lb. so that its horizontal component on a 1/100 gradient is 5.5×10^4 lb. or 25 tons. It should not be difficult to provide anchorages or rather stops at 400 ft. intervals each side of the runway strong enough to take a force of some 12 tons.

(f) Problem of filling bags with water

The operation of filling the bags should be made as simple as possible. One visualises the empty rubber bags laid flat on the floor of the runway with a rubber supply pipe integral with each bag and leading from a point on the under surface of the bag to the side of the runway. There will also be a short vertical rubber vent pipe in the upper surface of the bag, which pipe will pass through a hole in the slab element placed over it. A good sized steel-lined hole will be made in the slab to accommodate this pipe which will be placed at the highest point relative to any ground gradient there may be.

With the bags in position and the slab elements lined up and resting on them, the bags are then filled from the same head of water and the whole carpet is thereby lifted up to its operating position. In the course of this operation controlled bleeding of air and water will take place at the vent pipes.

(g) The purpose of the water-borne runway is not to complete with the conventional type of runway for aircraft up to 200,000 lb weight but to make it possible to contemplate the use of aircraft weighing two, three or four times that weight. With the water-borne type of runway the designer would have complete control of the situation and would not need to make what Mr. Cooper calls 'inspired guesses'.

The writer will now consider in detail the various points raised by commentators.

Mr. Laing doubts whether the cost (extra to the £200,000 for the water bags) of the constructional complications can be faced. Three complications in particular give rise to these doubts. The first—item (1) in his contribution—concerns the filling of the bags with water. He mentions the idea of filling the bags with water at some central filling station beforehand and goes on to say "Each of them would weigh approximately 6 short tons when filled with

water: so causing wellnigh insuperable difficulties", with which statement the writer thoroughly agrees.

On the other hand, he says, if the bags are filled 'in situ' "loading each of them with an accurately weighed amount of water and the sealing of the filling orifice will call for a very close control by the site staff". The answer to these fears is given by item (f) above.

Regarding his item (2) the first paragraph does not apply since precast slabs will be used. In the event of precast slabs being used Mr. Laing fears that the handling of 20' x 20' slabs will be difficult. The writer agrees but, in view of what is stated in item (c) above, this difficulty vanishes, since any convenient smaller size of slab will do equally well.

In his item (3) he expresses the fear that, since the present continuous sequence of operations (in current constructional work) would not apply, "each bay would have to be dealt with individually, so slowing down the rate of construction tremendously".

To this the writer would reply that, by adopting some such form and method of construction as that described in item (b) above, far from proving slower and more expensive than traditional methods, both cost and time may well be saved.

The validity of Mr. Laing's three objections are therefore highly questionable if not untenable; they are certainly not valid enough to condemn the scheme out of hand as he does.

Mr. Cooper gives the same kind of 'faint praise' and proceeds to make a number of remarks that, curiously enough, seem to contradict the point which he sets out to prove, namely, that the proposals "seem unlikely to be ever used in practice, and provide no more than an interesting theoretical exercise".

The writer has little to quarrel with what he says in the first three paragraphs of his contribution. In his fourth paragraph he refers to the Westergaard method of designing the concrete slabs and states that the method requires certain 'broad assumptions' (an oft-recurring phrase) to be made. The writer would ask 'Why broad assumptions?'; assumptions must of course be made but they should be based on sound experimental data. "If," he says "load transfer devices are used, further arbitrary assessment has to be made of their efficiency". But, why the qualifying adjective 'arbitrary'? Any load-transfer device would naturally have been thoroughly tested beforehand and should need no 'assessment'.

Mr. Cooper admits that the soil itself has extremely elusive properties and that some guesswork is involved in introducing the soil factor into the Westergaard formula. He concludes that the design of a concrete runway is an art rather than a science and that the engineer tends to rely on his experience rather than on theoretical calculations. Here the writer states that one of the main objects of this exercise was to get away from just such an unsatisfactory situation in which guesswork takes the place of precise calculation. For, if theoretical calculations are to be set aside in favor of past experience how, one asks, can advances ever be made, unless of course the expensive method of trial and error is adopted.

Mr. Cooper further remarks that advocates of prestressed concrete for pavements claim that this material would be ideal under just such soil condition as the writer visualise for the waterbags. The writer doubts that they do, but, if they do so claim, they are mistaken. A prestressed concrete pavement laid on poor soil could not long protect that soil from being knocked

out of shape by the dynamic impact of landing wheels, so that even if the pavement itself survived for a time the runway would soon become too uneven.

The points regarding a sloping site and deflections under load listed as items (a) and (b) by Mr. Cooper have already covered in items (d) and (e) above.

On the point of ducts under the runway to provide various services, such ducts could well be laid under the 5 ft cross strips separating the monolith carpets.

In the paper when reference was made to a possible military use for the water-borne principle the writer had in mind, and indeed specifically mentioned, temporary landing strips, not the runways 2000 yds by 50 yds, discussed by Mr. Cooper. What the writer was advocating was a landing strip of light wooden construction, with hexagonal slabs of 5 ft side (say) hinged at their upper edges and supported by bags 2 or 3 in. thick. Such a landing strip would behave largely as a homogeneous carpet, immune from the undulating effects visualized by Mr. Cooper, easily put up, and easily dismantled. The weight of water moreover would be modest.

Judging by his penultimate paragraph, Mr. Cooper seems to be living in the world of Lancasters and Halifaxes, where 12 in. of unprestressed concrete gave a respectable support. Apparently he has not realised that that sort of thickness is completely out of date for aircraft weighing 5 to 10 times the weight of a Lancaster.

Sir Morris Adams raises various practical points that would have to be watched and the writer agrees with what he says: In particular he has noted the point mentioned in item (a) above regarding the articulating effect of the shear joints on the deflections recorded in model tests.

Regarding the method suggested by Dr. Morice and Mr. Cooley, on which Sir Morris would like further information, Dr. Morice writes as follows:

> "There are really two different cases which were considered for the pre-stressed paving of a waterborne runway. Firstly, a pretensioned slab with a metal tongue shear connexion, very similar to Dr. Williams' original wooden model. It is this system which would probably be used for runways likely to receive local damage. Slabs would be very readily removed and replaced by unbolting the connections round the affected area. Secondly, a post-tensioned system in which prestressing cables would thread through two lengths of pre-cast slabs only in each direction in an overlapping arrangement so that each joint between the slabs would be under pre-compression. This scheme was suggested primarily to avoid very long cables with attendant site problems. Such a system was considered to be of a permanent nature and could only be arranged for subsequent slab removal by having the cables ungrouted—a somewhat unsatisfactory condition in our present state of knowledge as Sir Morris remarks. It is not inconceivable, however, that an adequate protection (such as p.v.c. coating to the wires) might be devised."

MEETING U.S.A.F. BLAST FENCE REQUIREMENTS[a]

Discussion by J. M. Merzweiler and C. A. Anderson

J. M. MERZWEILER,[1] and C. A. ANDERSON.[2]—Colonel Tucker is to be congratulated for introducing his readers to this timely and interesting subject. The subject is timely because commercial jet aircraft will soon be operating from many of our civil airports. Although the author confines his paper to the Air Forces' solution of the ground control of the jet blast from the B-52 bomber, the basic approach and principles developed are applicable for civil jet aircraft. The writers of this discussion assisted the Air Force in the conduct of the reported tests and in addition have also been associated with similarly conducted studies for the ground control of rocket and guided missile blasts. These studies and development work on the control of high temperature supersonic blasts have been in progress for the past six years at the Division Laboratories of the U. S. Army Engineer Division, Ohio River, Cincinnati, Ohio, and all of these studies substantiate principles which are applicable to most blast fence problems. These principles are given by the following statements:

1. Any surface (curved or flat) properly positioned will deflect jet engine blast. This deflected blast will continue in the turned direction until some external force is applied.
2. Assuming roughly horizontal blast being deflected upward by a "barricade" type of structure, two external forces are usually available to act on the deflected blast. These forces are:
   a. Pressure of some of the unturned jet stream passing over top of the turning surface, causing the final direction of deflected blast to be a component of the deflected and undeflected blasts.
   b. A low pressure area or partial vacuum on the down wake side of the turning device resulting in a differential pressure being applied to the deflected stream bending it down wake, but it is usually less significant than that caused by undeflected blast movement.
3. Blast force applied to the fence is equivalent to the proportion of energy of the blast stream intercepted by the fence surface exposed to the blast, multiplied by the engines thrust. The reaction force of the fence is found by the following equation:

$$R = T \sqrt{2\,(1 - \cos \Theta)}$$

where R = Reaction force.

a. Proc. Paper 1892, January, 1959, by Lt. Col. Temple A. Tucker.
1. Ohio River Div. Labs., Corps of Engrs., Cincinnati, Ohio.
2. Ohio River Div. Labs., Corps of Engrs., Cincinnati, Ohio.

T = Blast force applied to the fence.

θ = Angle of deflection.

The direction of this reaction on simple turning surfaces is found by bisecting the angle formed by the tangents of the leading and exit ends of the turning surface.

4. A single-turning surface-type of blast fence is as efficient as a multiple-vane type if the same proportion of total blast is intercepted by the fence, with the following exceptions:

   a. In a multiple-vane type, the vane supports can usually be oriented to coincide with the direction of the reaction force from the blast, eliminating the need for a second system of blast load supports for the fence; whereas in a single-turning surface-type the reaction force invariably falls outside the structure, usually requiring supports or anchors to overcome this over-turning force, especially in a light weight fence.

   b. Blast impinging on any surface spreads laterally. In the single-turning surface-type fence this lateral spread usually causes an undesirable blast effect beyond the ends of a given length of fence. This can be alleviated by adding lateral bulkheads on the turning surface of such dimensions and spacing to break up this lateral flow. Fig. 33 of the author's paper shows these bulkheads at a maximum spacing. The multiple-vane fence utilizes the vane supports to prevent lateral spread.

   c. When a blast is intercepted by a surface turning the blast 30° or more, a pressure front is built up on the turning surface resulting in a flow in all directions. With multi-louvered fences each component of blast back toward the source is redirected to the original direction by the blast below each turning surface. In single-vane turning surfaces the blast back toward the source can be of major magnitude because all of the adversely turned gases under optimum conditions will continue in the originally turned direction.

5. Smoothly curved or segmentally curved turning surfaces are both structurally and aerodynamically superior to flat turning surfaces. In cases where the engines are close enough to a blast fence for heat to be a problem, smoothly curved surfaces will withstand heat better than segmentally curved or flat turning surfaces. Regardless of the material used for a blast fence, the designer should select a safe allowable stress based upon the temperature that can be anticipated in the structure (a function of power and spacing). For all but severe cases hot-rolled steel has proven satisfactory. The use of light weight alloys should be used only after careful investigation.

6. In the case of the Air Force requirements, the underside of the deflected blast was required to clear parked aircraft resulting in an angle roughly 60° from the horizontal. Therefore, openings 1/3 of the vane height between vanes in a multiple-vane fence, or interception of about 2/3 of the total blast, proved to furnish a satisfactory angle of blast deflection. In general any other angle of turning can be predicted fairly closely by the selected deflection angle of the structure and by the proportional amount of blast that is intercepted, provided sufficient clearance exists between the deflected blast and the ground to permit

ambient or static air to relieve the low pressure area to the rear of the fence. If the deflected blast is too close to the ground surface the low pressure area tends to build up, resulting in the deflected blast "locking onto" and following the ground surface. For the prototype conditions tested, this critical condition was being approached in the one fence which necessitated raising the leading edge.

The above statements of principles and experience with blast fence development together with the data presented in the paper should prove of value in evaluating the efficiency and stability of available types of blast fences and newly developed fences for a specific set of conditions.

VTOL-STOL AIRCRAFT[a]

Corrections

CORRECTIONS.—On page 6 of Proceedings Paper 2102 from the July Journal of the Air Transport Division, delete the name, and position of Howard G. Law on Line 3 and substitute:

> Charles D. House, LaGuardia Air Carrier Safety District Office, Federal Aviation Agency, LaGuardia Airport, Flushing 71, New York.

On page 8, in paragraph 3, delete all of the material from line 1 down through the words "of the prevailing winds will suffice" on line 27. In place of the deleted material substitute the following:

> Next let us look at the probable landing and take-off requirements of the aircraft and its maneuvering ability on the ground. We have established an operating perimeter of a circle having a diameter of 140 feet so the landing and take-off area will be a function of some length by a width of 140 feet. As air currents will affect the exact location of the aircraft the moment it is airborne, side clearances should be provided similar to those for a runway. A side slope one on one from the edge of the take-off area to a height of 50 feet should be provided for the length of the take-off area. It should be borne in mind that the aircraft must obtain sufficient height over the landing area to clear surrounded obstructions and to fly a precise flight-pattern or to return to the landing area should mechanical difficulty demand. Present indications are that the take-off maneuver will not be a vertical climb for several hundred feet and then converting to horizontal flight but rather a steep ascent which will combine forward acceleration and vertical climb. A ratio of four feet horizontal to 1 foot vertical is the suggested flight pattern for take-off. While there is little doubt that by 1970-75 the aircraft will achieve one engine out performance there is wide divergence of opinion as to what the flying capabilities of the aircraft will be. There is no doubt that for passenger service the operation must be safe. It is suggested that the aircraft should obtain an altitude of 100 feet before it loses the ability to return to the landing area. A vertical ascent to a height sufficient to obtain the necessary forward velocity to continue flight in case of an engine failure would require the length of the landing area to approximately 400 feet for the 1975 aircraft. The aircraft will be capable of operating with cross-wing components of such magnitude that for practical purposes a landing area oriented in the direction of the prevailing winds will suffice.

a. Proc. Paper 2102, July, 1959, by the Committee on Air Centers.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Department of Conditions of Practice are identified by the symbols (PP). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper number are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 1859 is identified as 1859 (HY7) which indicates that the paper is contained in the seventh issue of the Journal of the Hydraulics Division during 1958.

VOLUME 84 (1958)

OCTOBER: 1790(EM4), 1791(EM4), 1792(EM4), 1793(EM4), 1794(EM4), 1795(HW3), 1796(HW3), 1797(HW3), 1798(HW3), 1799(HW3), 1800(HW3), 1801(HW3), 1802(HW3), 1803(HW3), 1804(HW3), 1805(HW3), 1806(HY5), 1807(HY5), 1808(HY5), 1809(HY5), 1810(HY5), 1811(HY5), 1812(SM4), 1813(SM4), 1814(ST6), 1815(ST6), 1816(ST6), 1817(ST6), 1818(ST6), 1819(ST6), 1820(ST6), 1821(ST6), 1822(EM4), 1823(PO5), 1824(SM4), 1825(SM4), 1826(SM4), 1827(ST6)[c], 1828(SM4)[c], 1829(HW3)[c], 1830(PO5)[c], 1831(EM4)[c], 1832(HY5)[c].

NOVEMBER: 1833(HY6), 1834(HY6), 1835(SA6), 1836(ST7), 1837(ST7), 1838(ST7), 1839(ST7), 1840(ST7), 1841(ST7), 1842(SU3), 1843(SU3), 1844(SU3), 1845(SU3), 1846(SU3), 1847(SA6), 1848(SA6), 1849(SA6), 1850 (SA6), 1851(SA6), 1852(SA6), 1853(SA6), 1854(ST7), 1855(SA6)[c], 1856(HY6)[c], 1857(ST7)[c], 1858(SU3)[c].

DECEMBER: 1859(HY7), 1860(IR4), 1861(IR4), 1862(IR4), 1863(SM5), 1864(SM5), 1865(ST8), 1866(ST8), 1867 (ST8), 1868(PP1), 1869(PP1), 1870(PP1), 1871(PP1), 1872(PP1), 1873(WW5), 1874(WW5), 1875(WW5), 1876 (WW5), 1877(CP2), 1878(ST8), 1879(ST8), 1880(HY7)[c], 1881(SM5)[c], 1882(ST8)[c], 1883(PP1)[c], 1884(WW5)[c], 1885(CP2)[c], 1886(PO6), 1887(PO6), 1888(PO6), 1889(PO6), 1890(HY7), 1891(PP1).

VOLUME 85 (1959)

JANUARY: 1892(AT1), 1893(AT1), 1894(EM1), 1895(EM1), 1896(EM1), 1897(EM1), 1898(EM1), 1899(HW1), 1900(HW1), 1901(HY1), 1902(HY1), 1903(HY1), 1904(HY1), 1905(PL1), 1906(PL1), 1907(PL1), 1908(PL1), 1909(ST1), 1910(ST1), 1911(ST1), 1912(ST1), 1913(ST1), 1914(ST1), 1915(ST1), 1916(AT1)[c], 1917(EM1)[c], 1918(HW1)[c], 1919(HY1)[c], 1920(PL1)[c], 1921(SA1)[c], 1922(ST1)[c], 1923(EM1), 1924(HW1), 1925(HW1), 1926 (PL1), 1927(HW), 1928(HW1), 1929(SA1), 1930(SA1), 1931(SA1), 1932(SA1).

FEBRUARY: 1933(HY2), 1934(HY2), 1935(HY2), 1936(SM1), 1937(SM1), 1938(ST2), 1939(ST2), 1940(ST2), 1941(ST2), 1942(ST2), 1943(ST2), 1944(ST2), 1945(HY2), 1946(PO1), 1947(PO1), 1948(PO1), 1949(PO1), 1950(HY2)[c], 1951(SM1)[c], 1952(ST2)[c], 1953(PO1)[c], 1954(CO1), 1955(CO1), 1956(CO1), 1957(CO1), 1958(CO1), 1959(CO1).

MARCH: 1960(HY3), 1961(HY3), 1962(HY3), 1963(IR1), 1964(IR1), 1965(IR1), 1966(IR1), 1967(SA2), 1968(SA2), 1969(ST3), 1970(ST3), 1971(ST3), 1972(ST3), 1973(ST3), 1974(ST3), 1975(ST3), 1976(WW1), 1977(WW1), 1978(WW1), 1979(WW1), 1980(WW1), 1981(WW1), 1982(WW1), 1983(WW1), 1984(SA2), 1985(SA2)[c], 1986 (IR1)[c], 1987(WW1)[c], 1988(ST3)[c], 1989(HY3)[c].

APRIL: 1990(EM2), 1991(EM2), 1992(EM2), 1993(HW2), 1994(HY4), 1995(HY4), 1996(HY4), 1997(HY4), 1998 (SM2), 1999(SM2), 2000(SM2), 2001(SM2), 2002(ST4), 2003(ST4), 2004(ST4), 2005(ST4), 2006(PO2), 2007 (HW2)[c], 2008(EM2)[c], 2009(ST4)[c], 2010(SM2)[c], 2011(SM2)[c], 2012(HY4)[c], 2013(PO2)[c].

MAY: 2014(AT2), 2015(AT2), 2016(AT2), 2017(HY5), 2018(HY5), 2019(HY5), 2020(HY5), 2021(HY5), 2022(HY5), 2023(PL2), 2024(PL2), 2025(PL2), 2026(PP1), 2027(PP1), 2028(PP1), 2029(PP1), 2030(SA3), 2031(SA3), 2032(SA3), 2033(SA3), 2034(ST5), 2035(ST5), 2036(ST5), 2037(ST5), 2038(PL2), 2039(PL2), 2040(AT2)[c], 2041(PL2)[c], 2042(PP1)[c], 2043(ST5)[c], 2044(SA3)[c], 2045(HY5)[c], 2046(PP1), 2047(PP1).

JUNE: 2048(CP1), 2049(CP1), 2050(CP1), 2051(CP1), 2052(CP1), 2053(CP1), 2054(CP1), 2055(CP1), 2056 (HY6), 2057(HY6), 2058(HY6), 2059(IR2), 2060(IR2), 2061(PO3), 2062(SM3), 2063(SM3), 2064(SM3), 2065 (ST6), 2066(WW2), 2067(WW2), 2068(WW2), 2069(WW2), 2070(WW2), 2071(WW2), 2072(CP1)[c], 2073(IR2)[c], 2074(PO3)[c], 2075(ST6)[c], 2076(HY6)[c], 2077(SM3)[c], 2078(WW2)[c].

JULY: 2079(HY7), 2080(HY7), 2081(HY7), 2082(HY7), 2083(HY7), 2084(HY7), 2085(HY7), 2086(SA4), 2087 (SA4), 2088(SA4), 2089(SA4), 2090(SA4), 2091(EM3), 2092(EM3), 2093(EM3), 2094(EM3), 2095(EM3), 2096 (EM3), 2097(HY7)[c], 2098(SA4)[c], 2099(EM3)[c], 2100(AT3), 2101(AT3), 2102(AT3), 2103(AT3), 2104(AT3), 2105(AT3), 2106(AT3), 2107(AT3), 2108(AT3), 2109(AT3), 2110(AT3), 2111(AT3), 2112(AT3), 2113(AT3), 2114(AT3), 2115(AT3), 2116(AT3), 2117(AT3), 2118(AT3), 2119(AT3), 2120(AT3), 2121(AT3), 2122(AT3), 2123(AT3), 2124(AT3), 2125(AT3).

AUGUST: 2126(HY8), 2127(HY8), 2128(HY8), 2129(HY8), 2130(PO4), 2131(PO4), 2132(PO4), 2133(PO4), 2134 (SM4), 2135(SM4), 2136(SM4), 2137(SM4), 2138(HY8)[c], 2139(PO4)[c] 2140(SM4)[c].

SEPTEMBER: 2141(CO2), 2142(CO2), 2143(CO2), 2144(HW3), 2145(HW3), 2146(HW3), 2147(HY9), 2148(HY9), 2149(HY9), 2150(HY9), 2151(IR3), 2152(ST7)[c], 2153(IR3), 2154(IR3), 2155(IR3), 2156(IR3), 2157(IR3), 2158 (IR3), 2159(IR3), 2160(IR3), 2161(SA5), 2162(SA5), 2163(ST7), 2164(ST7), 2165(SU1), 2166(SU1), 2167(WW3), 2168(WW3), 2169(WW3), 2170(WW3), 2171(WW3), 2172(WW3), 2173(WW3), 2174(WW3), 2175(WW3), 2176 (WW3), 2177(WW3), 2178(CO2)[c], 2179(IR3)[c], 2180(HW3)[c], 2181(SA5)[c], 2182(HY9)[c], 2183(SU1)[c], 2184 (WW3)[c], 2185(PP2)[c], 2186(ST7)[c], 2187(PP2), 2188(PP2).

OCTOBER: 2189(AT4), 2190(AT4), 2191(AT4), 2192(AT4), 2193(AT4), 2194(EM4), 2195(EM4), 2196(EM4), 2197(EM4), 2198(EM4), 2199(EM4), 2200(HY10), 2201(HY10), 2202(HY10), 2203(PL3), 2204(PL3), 2205 (PL3), 2206(PO5), 2207(PO5), 2208(PO5), 2209(PO5), 2210(SM5), 2211(SM5), 2212(SM5), 2213(SM5), 2214 (SM5), 2215(SM5), 2216(SM5), 2217(SM5), 2218(ST8), 2219(ST8), 2220(EM4), 2221(ST8), 2222(ST8), 2223 (ST8), 2224(HY10), 2225(HY10), 2226(PO5), 2227(PO5), 2228(PO5), 2229(ST8), 2230(EM4), 2231(EM4), 2232(AT4)[c], 2233(PL3)[c], 2234(EM4)[c], 2235(HY10)[c], 2236(SM5)[c], 2237(ST8)[c], 2238(PO5)[c], 2239(ST8), 2240 (PL3).

c. Discussion of several papers, grouped by divisions.